UNIVERSIDAD COMPLUTENSE DE MADRID
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TESIS DOCTORAL

Contributions to the Configuration of Fleets of Robots for Precision Agriculture

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

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UNIVERSIDAD COMPLUTENSE DE MADRID

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PhD Thesis

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Tesis Doctoral / PhD Thesis

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Contributions to the Configuration of Fleets of Robots for Precision Agriculture

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Memoria presentada para optar al grado de Doctor por
Dissertation submitted to obtain the PhD Degree by

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Madrid, 2014

A mi familia que lo es todo para mí

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Abstract

Precision Agriculture (PA) aims to the application of selective treatments as well as the use of agricultural inputs depending on the field and crop needs spatially localized. One of the most demanded agricultural work is the effective weed control, to increase productivity while decreasing the usage of polluting chemical products. The incorporation of new positioning technologies (GPS, Laser), acquisition and detection (computer vision) and automatic control adapted for vehicles (tractors) and for agricultural machinery (implements), has established the foundation for the development of PA. Although, only a few cases have achieved a configuration of a fully autonomous agricultural system, and with a minor dimension, a configuration of a fleet of robots for cooperation and for distribution of agricultural tasks.

The study presented in this research includes three major contributions oriented to the aforementioned automation. More specifically, this research provides the foundation through the development of a control architecture for the integration of both an autonomous vehicle and an autonomous implement, endowed with the technology required to achieve such autonomy and efficient performance.

The first contribution is the development of a simulation environment to study and evaluate the implementation of PA techniques that allows the performance, cooperation and interaction of a group of autonomous robots to be analyzed, while the execution of a specific task is simulated in a three-dimensional world. This simulation environment allows the real characteristics of a defined field or crop to be represented (obtained by measurements or downloaded via online databases), and diverse variabilities that may affect the accuracy in the task of the fleet of robots to be modeled. This simulation environment has proven to be a perfect tool for configuring and validating the design concepts proposed in this research.

The second contribution is the development of a proposal of a control architecture to integrate a vehicle equipped with an implement, with the purpose to constitute a fully autonomous agricultural unit able to work cooperatively in a fleet of robots. For their achievement, the characteristics of the required configuration has been identified, complying with specifications of hardware reliability, modularity, expandability, ergonomics, maintenance, and cost, for the purpose of providing the manufacturers of agricultural machinery with solutions for automating new developments in the area of PA. The results obtained, both qualitative and quantitative, confirm the validity of the proposal.

The third contribution is the integration and validation, in a real crop field, of a perception system (based on computer vision and GPS location), an actuation system (consisting of an autonomous tractor and an autonomous implement for mechanical weed control) and a decision-making system (which is the core of the integration of these elements), all encompassed in the control architecture developed from the perspective of full autonomy. This integration was performed using the selection, management, configuration and synchronization of these systems, providing a model for a fully autonomous vehicle for agricultural applications. Successful results of several experiments conducted on real crop fields in different seasons and under different crop conditions are presented, demonstrating the performance and validity of the integrated proposal in guidance and weed control tasks in a maize field, and its usefulness and effectiveness.

This work is a major advance in the design of mobile units able to work in coordination as a fleet of robots in agricultural tasks, resulting in several publications in various scientific journals and prestigious international conferences in the area of PA. The developments obtained have been a fundamental part in the progress of the RHEA project, demonstrating the ability to configure a fleet of robots for PA applications, having been endorsed by members of the project consortium, as well as positive evaluations of the representatives of the European Union, both technical and management.

Resumen

La Agricultura de Precisión (AP) tiene como finalidad la aplicación de tratamientos selectivos, así como el uso de insumos agrícolas dependiendo de las necesidades espacialmente localizadas del terreno y el cultivo. Una de las tareas agrícolas más demandadas es la gestión efectiva de las malas hierbas, con el fin de incrementar la productividad a la vez que se reduce el uso de productos químicos contaminantes. La incorporación de nuevas tecnologías de posicionamiento (GPS, Láser), adquisición y detección (visión por computador) y control automático adaptados a vehículos (tractores) y a maquinaria agrícola (implementos) ha permitido establecer las bases para el desarrollo de la AP. Si bien sólo en unos pocos casos se ha logrado un sistema totalmente autónomo y en menor medida la utilización de una flota de robots para la cooperación y la distribución de tareas agrícolas.

El estudio que se presenta en este trabajo de investigación recoge tres importantes aportaciones de cara a la mencionada automatización. Más específicamente, establece las bases, mediante el desarrollo de una arquitectura de control, para la integración de un vehículo y un implemento ambos autónomos, dotados con las tecnologías requeridas para lograr dicha autonomía y unas prestaciones eficientes.

La primera aportación consiste en el desarrollo de un entorno de simulación para estudiar y evaluar la implementación de técnicas de AP, que permiten el análisis del desempeño, la cooperación y la interacción de un conjunto de robots autónomos mientras se simula la ejecución de tareas específicas en un mundo en tres dimensiones. Este entorno de simulación permite representar las características reales de un campo de cultivo definido (obtenidas mediante mediciones o descargadas a través de bases de datos en línea) para el modelado de diferentes variabilidades que pueden afectar a la exactitud en el cometido de tareas de la flota de robots. Este entorno ha demostrado ser una herramienta perfecta muy apropiada para configurar y validar el diseño de los conceptos propuestos en este trabajo de investigación.

La segunda aportación es el desarrollo de una propuesta de arquitectura de control con el propósito de integrar un vehículo equipado con un implemento para formar una unidad agrícola totalmente autónoma, capaz de trabajar en cooperación en una flota de robots. Para su consecución se han identificado las características de la configuración necesaria cumpliendo con especificaciones relativas a fiabilidad del hardware, modularidad, capacidad de expansión, ergonomía, mantenimiento, y coste, con el propósito de proveer a los fabricantes de maquinaria agrícola soluciones para la automatización de nuevos desarrollos en el área de la AP. Los resultados obtenidos, tanto cualitativos como cuantitativos, confirman la validez de la propuesta.

La tercera aportación consiste en la integración y validación, en un campo de cultivo real, de un sistema de percepción (basado en visión por computador y localización mediante GPS), un sistema de actuación (compuesto por un tractor y un implemento autónomo para el control mecánico de malas hierbas) y un sistema de toma de decisiones (que constituye el núcleo de la integración de dichos elementos), todos ellos englobados en la arquitectura de control desarrollada bajo la perspectiva de autonomía total. Esta integración se ha realizado mediante la selección, la ordenación, la configuración y la sincronización de dichos sistemas, lo que proporciona un modelo para un vehículo completamente autónomo para aplicaciones agrícolas. Se presentan resultados significativos de diversos experimentos realizados en campos de cultivo reales, en diferentes épocas del año y bajo diferentes condiciones del cultivo, demostrando el rendimiento y validez de la propuesta integrada en tareas de guiado y control de malas hierbas en un campo de maíz, así como su utilidad y eficacia.

Este trabajo ha supuesto un avance importante en el diseño de unidades móviles capaces de trabajar coordinadamente como flotas de robots en tareas agrícolas, que ya han dado lugar a diferentes publicaciones científicas en revistas y congresos internacionales de prestigio en el área de la AP y la robótica. Los desarrollos obtenidos han sido parte fundamental en el progreso del proyecto RHEA, demostrando las capacidades para configurar una flota de robots para tareas agrícolas en AP, habiendo sido avalados por los miembros integrantes del proyecto, así como por las evaluaciones positivas de los representantes de la Unión Europea, tanto técnicos como de gestión.

Note to the Reader

This Thesis is structured as follows:

Part I is the main part of the Thesis, and it is written in English. It describes (1) the motivations, objectives, and contributions of this Thesis; (2) a summary of the use of autonomous systems in Precision Agriculture; (3) a description of the design and development of a simulation environment for the evaluation of Precision Agriculture techniques using autonomous vehicles; (4) the development of a system architecture for autonomous agricultural vehicles in a fleet of robots; (5) the integration of perception, actuation, and decision making as subsystems for an agricultural autonomous system; (6) the conclusions of this Thesis and future work.

Part II is a summary of Part I, and it is written in Spanish. It contains (1) the motivations, objectives, and contributions of this Thesis; (2) an overview of the development of a simulation environment for the evaluation of Precision Agriculture techniques using autonomous vehicles; (3) a brief explanation of the development of a control architecture for autonomous agricultural robots; (4) a summary of the contributions derived for the integration of perception, actuation, and decision making as subsystems for an agricultural autonomous system; (5) the conclusions of this Thesis and future work.

Nota al Lector

Esta memoria de tesis contiene la siguiente estructura:

Parte I es la parte principal de esta memoria de tesis y se encuentra escrita en inglés. En ella se presenta lo siguiente: (1) las motivaciones, objetivos y contribuciones de esta tesis; (2) una revisión del uso de sistemas autónomos en la Agricultura de Precisión; (3) una descripción del diseño y desarrollo de un entorno de simulación para la evaluación de técnicas de Agricultura de Precisión mediante el uso de vehículos autónomos; (4) el desarrollo de una arquitectura de sistema para vehículos agrícolas autónomos en una flota de robots; (5) la integración de la percepción, actuación y toma de decisiones como subsistemas de un sistema agrícola autónomo; y (6) las conclusiones y el trabajo futuro de esta tesis.

Parte II es un resumen en Español de la Parte I. En ella se presenta lo siguiente: (1) las motivaciones, objetivos y contribuciones de esta tesis; (2) una visión general del desarrollo de un entorno de simulación para la evaluación de técnicas de Agricultura de Precisión mediante el uso de vehículos autónomos; (3) una pequeña explicación del desarrollo de una arquitectura de control para robots agrícolas autónomos; (4) un resumen de las contribuciones derivadas de la integración de la percepción, actuación y toma de decisiones como subsistemas de un sistema agrícola autónomo; y (5) las conclusiones y el trabajo futuro de esta tesis.

Contents

Part I: Contributions to the Configuration of Fleets of Robots for Precision Agriculture

Chapter 1

Introduction

1.1. The Need for Automation in Agriculture

Over the last 50 years, the global population has doubled while land under cultivation has increased by only approximately 12 percent. Even so, according to a yearly report by the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2012), global crop production has expanded threefold over the same time period thanks to higher yields per unit of land and crop intensification. One of the important elements that have enabled this increase in agricultural production worldwide has been a higher utilization of fertilizers and pesticides. However, abusing these inputs can lead to negative results on the environment and on the health of humans and animals. The most recommended approach for the proper employment of pesticides and fertilizers is called Integrated Pest Management (IPM), which mainly consists of the use of pest population information to estimate losses and to adjust the intervention doses accordingly. IPM is an economically justified ecological approach to crop management that reduces and minimizes risks to both human health and to the environment, emphasizes the growth of a healthy crop with the smallest possible disruption to agro ecosystems and encourages natural pest control mechanisms (FAO, 2012).

Although IPM is an efficient technique for reducing the use of pesticides while maintaining high productivity, it mainly considers the development, evolution and type of infestation over time (e.g., pest behaviors and reproductive cycles and plant pathogen responses to weather and season) in an entire field. Nevertheless, in the 1970s and 1980s, new methodologies helped researchers to better understand soil and crop condition variability within fields (Robert, 2002). One of the most important outcomes, as a result of this new knowledge, was being able to perceive the potential benefits of crop management by zones within fields rather than through the management of whole fields, as applied in IPM techniques.

Several names have been given to this type of practice (Cook and Bramley, 1998; Murakami et al., 2007), including site-specific management, site-specific farming, and precision farming. However, the range of methodologies that aim to optimize agricultural field management is commonly known as Precision Agriculture, and it focuses on the enhancement of agricultural management in three main areas: crop knowledge, environmental protection and economics. Precision Agriculture is an agricultural management concept that relies on observing and responding to field variations or variabilities. It is based on modern technologies, such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), Inertial Measurement Units (IMU), microcomputers, automatic control, in-field and remote sensing, mobile computing, advanced information processing, and telecommunications, which all offer great benefits in the acquisition, processing, and utilization of spatial field data for the purposes of applying these management principles to managing the in-field variability of soils and crops (Zhang et al., 2002).

To manage the unpredictability/variability within a field, and because of new advances in sensors, computer vision and control systems over the past two decades, multiple research trends have arisen from the idea of developing agricultural robots for cultivation, harvesting, and pest control (Mousazadeh, 2013). Such autonomous systems allow field information acquisition to be more accurate (Lee et al., 2010), automatic weed control to be more effective to ensure the safety of the crop (Bakker, 2009; Tian, 2002), and harvesting and transplanting to be more precise and efficient (Nagasaka et al., 2009; Pilarski et al., 2002).

By focusing on autonomous mobile systems oriented toward site-specific crop management, we can analyze the problem by dividing a robotic unit into two main elements: the element that gives mobility to the agricultural system (the vehicle) and the element that performs the treatment (the implement). An autonomous vehicle, such as a modified commercial tractor, specialized platform or small vehicle, guides the agricultural system in a crop field for the purpose of executing a specific task (e.g., harvesting, hoeing, or weed control), which will be accomplished by the autonomous implement. Due to the complexity of the assignment, both elements must work in accordance and in sync, and a large number of specialized sensors and actuators are required to fulfill a given task in a given environment (e.g., outdoor fields or semi-structured working area). This integration of an autonomous vehicle with an automated implement, as well as sensory, actuation and decision-making systems, **can be defined as a fully autonomous agricultural system.**

Because of the nature of farming, the vehicles have to exhibit robustness, reliability and flexibility, and they must be capable of being applied to all types of farm work, including weed control, the area that this research focuses on. Thus, in general terms, the same vehicle can be used to perform different agricultural tasks depending on the implement that it carries. By performing a review of the research from recent years related to solving the autonomous guidance problem, i.e., the automation and control of agricultural vehicles, we found that intense research activity has been documented in the literature (Keicher and Seufert, 2000; Li et al., 2009; Reid et al., 2000). Moreover, a considerable amount of research activities can be found concerning intelligent implements for weed control (Comba et al., 2010), which are part of all developments on autonomous implements for agricultural tasks in general. However, only a few attempts to establish a fully autonomous agricultural system by integrating an autonomous vehicle and an autonomous implement can be found in the scientific literature. Many authors agree that this is the future of automation in agriculture (Auat Cheein and Carelli, 2013; Bergerman et al., 2012; Johnson et al., 2009; Noguchi and Barawid Jr, 2011; Vougioukas, 2012), whereby a single system or a set of fully autonomous robotic systems perform the most arduous agricultural tasks, allowing the operator to focus on planning and supervision rather than on guiding a tractor or on controlling the implement. These tasks have been demonstrated to be executed with higher accuracy by robotic systems than by human operators with a significant increase in productivity (Moorehead et al., 2012).

Making a general review on the scientific literature, two clear approaches can be identified for the selection of the morphology of a fully autonomous agricultural system:

1. **The small-sized robot approach**, which is the most abundant in the literature, consists of mobile platforms or very small tractors. These types of vehicles have the advantage of being more precise than larger machines, given that these vehicles have a higher maneuverability and a higher

capability for performing selective treatment in small areas. Additionally, small vehicles are lighter than larger vehicles, providing energy savings in mobility and soil compaction reduction. By contrast, these types of vehicles have a lower work rate, requiring more working hours or more vehicles for the execution of the same amount of work. Another disadvantage is the lack of robustness, whereby they are unable to perform for long periods of time under very demanding working conditions (i.e., in presence of stones, ditches, trees, etc.).

2. **The medium-sized robot approach**, which consists of mostly modified commercial tractors that can carry heavier implements and that are able to work lager areas than can smaller vehicles. Because commercial tractors come from a factory with standard elements electronically controlled (connections such as the three-point hitch, hydraulic and electrical power, and power take off), only a few modifications are needed to make the tractor work autonomously. Another advantage of the use of large vehicles is the intrinsic robustness of the commercial tractors, allowing the vehicle to maintain a high rate of work regardless of the environmental and terrain conditions. On the contrary, these types of vehicles require more safety features because of their size and power and because of the potential harm that they can do.

The vast majority of studies have served to design and develop new algorithms and new specialized machinery, where most of these studies are focused solely on key elements of what would become a fully autonomous agricultural system (e.g., guidance, crop or weed detection, and selective treatment). Furthermore, several authors have presented conceptual approaches of hardware/software architectures for establishing a fully autonomous agricultural system (Auat Cheein et al., 2013; Bakker et al., 2010a; Blackmore et al., 2001; Fountas et al., 2007; Katupitiya et al., 2007; Rovira-Más, 2010a), and only some of them have implemented a full integration of an autonomous agricultural system and tested it under real-world conditions (Bergerman et al., 2012; Blackmore et al., 2004; Johnson et al., 2009; Kohanbash et al., 2012; Moorehead et al., 2012; Nørremark et al., 2008; Pilarski et al., 2002). In addition, this is one of the pathways that must be followed to put into practice (on real fields and for farmers) the integration of the large number of technologies and developments generated in recent years for the application of Precision Agriculture techniques. This integration can be used to demonstrate the capabilities that a fully autonomous agricultural system, or a group of them working together, is able to offer for a better use of inputs in modern agriculture.

Additionally, considering the current need for a more efficient application of chemicals and mechanization techniques for increasing productivity, reducing damage to the environment and preserving the health of humans and animals, this Thesis focuses on the study of how different elements enabling the execution of Precision Agriculture techniques, an improvement on IPM, can be applied, unified, and integrated using mobile robots, with a special focus on the reduction in the use of products for weed control in intensive crops. Given both approaches for the morphology of what should be a fully autonomous agricultural system (small-sized robots or platforms, or medium-sized robots or tractors), this dissertation presents a hardware/software architecture oriented toward solving the integration problem of the second approach. The selection of a diverse number of components and the elements that constitute this architecture was oriented toward introducing a fully autonomous agricultural system into industry.

Using the previous approach, this work presents a research proposal in the field of autonomous navigation and control for mobile units and implements applied to Precision Agriculture and investigates the most appropriate architectures and methodologies for agricultural environments from the viewpoint of automation.

An important aspect of constructing a robotic unit capable of executing agricultural tasks is the ability to integrate the necessary agricultural knowledge. Therefore, the first step in the research is the development of a simulation environment that enables the integration of robotics with agriculture. After developing the simulation environment, a hardware architecture is designed and implemented for mobile autonomous vehicles collaborating as a fleet of robots in agricultural tasks to meet hardware reliability, truly plug-and-play feature, and programmability requirements as well as modularity, expandability, ergonomic, maintenance, and cost requirements, which are also of paramount importance in increasing the number of prospective real applications in agriculture for the use of a real fleet of autonomous robots. The last step in the development of the research is the selection, arrangement, integration, and synchronization of several systems to form a fully autonomous agricultural system. Furthermore, experimental results are presented that are used to assess the designed hardware architecture through both quantitative and qualitative analyses associated with both hardware element reduction and with software development minimization in a single, fully autonomous agricultural system. Additionally, this work presents the results of an algorithm for collision avoidance, which was developed to allow the assessment of the benefit of hardware reduction in an agricultural fleet of robots for the execution of cooperative tasks. Moreover, this Thesis presents these experimental results to demonstrate the success and performance of the integrated system in vehicle guidance and weed control tasks in a real maize field, and its utility and efficiency are also reported.

1.2. Motivation and Scope

There has been a significant amount of progress in the last 20 years in the areas of weed detection, precision guidance, and selective treatment. However, many of these studies have only focused on the development and only put to work a single element of the entire system. As discussed in the previous section, there is a clear need for the integration of all of these elements (acquisition, guidance, decision making and actuation) to establish a fully autonomous agricultural system. One motivation of the work described in this dissertation is to present an alternative for the selection, arrangement, integration, and synchronization of these elements to form a complete autonomous system for agricultural applications. The elements that are required to comprise such a system come from different research areas and from diverse research groups (agronomist, roboticist, automation and control, machine vision, etc.). Therefore, the integration task requires a multidisciplinary approach, whereby each discipline has to work with different technologies, operating systems, programming languages, methodologies, etc.

The concept of a fully autonomous agricultural system in addition to the idea of using multiple robots to improve the performance of some tasks is not new. Currently some universities, research groups, and small and large companies, aided by large projects funded by the European community and large countries, are looking to bring this concept into practice. This is the case of the *Robot Fleets for Highly Effective Agriculture and Forestry Management* (RHEA) project funded under the European Union through the Seventh Framework Program and the *Integrated Automation for Sustainable Specialty Crops Farming* project founded by the United State Department of Agriculture (USDA).

The RHEA project focuses on the design, development, and testing of a new generation of automatic and robotic systems for effective chemical and physical weed management, which is applicable to both agriculture and forestry (Peruzzi et al., 2011; RHEA, 2014). In contrast, the project founded by the USDA focuses on the development of unmanned tractors, which are ideal platforms for Precision Agriculture technologies, for capturing information about tree canopies that will be used for target spraying of individual trees, estimating fruit yields, and detecting outbreaks of tree diseases (NREC, 2014). Thus, another motivation of the research is to present an approach for integrating diverse elements that make possible a fully autonomous agricultural system, following the medium-sized robot approach, which is a clear commitment on the part of the *Integrated Automation for Sustainable Specialty Crops Farming*[1] project and the RHEA consortium[2].

The evaluation of the proposed architecture has been carried out using the complete RHEA fleet, which provided real equipment (three automated tractors, computer vision, localization systems, obstacle detection systems and three different automated agricultural implements) for conducting the real-world tests. This has provided an essential benefit, allowing us to focus on the research, testing and validation of algorithms and methods for navigation and selective treatment rather than on working on the development of equipment.

The type of application and the environment in which the fully autonomous agricultural system has to interact define a specific navigation and actuation problem. Some studies have developed mobile platforms or small autonomous tractors, whereby the control architecture is adapted for a specific application and in some cases can be expanded to others systems. Normally, these robots are small-sized platforms, and they execute the treatment in small areas in the field simultaneously (e.g., the space under the platform). Given this current scenario, it is necessary to consider whether any of these architectures solves the problem addressed for full autonomy. Therefore, another motivation of the research is the opportunity to put into practice the developed control architecture in a real field, oriented toward the execution of precision tasks for weed control.

[1] The partners involved in this project are The National Robotics Engineering Center, John Deere, the University of Florida, and Cornell University.

[2] The partners involved in this project are Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC), CogVis GmbH, Forschungszentrum Telekommunikation Wien Ltd. (FTW), Cyberbotics Ltd, Università di Pisa, Universidad Complutense de Madrid, Tropical, Soluciones Agrícolas de Precisión S.L., Universidad Politécnica de Madrid (UPM), AirRobot GmbH & Co. KG, Università degli Studi di Firenze, IRSTEA, Case New Holland Industrial N.V., Bluebotics S.A., CM Srl.

The scope of this Thesis, which coincides with the scope of the RHEA project (Gonzalez-de-Santos et al., 2012; Peruzzi et al., 2011), is the development of new robotic concepts for building a fleet of autonomous robots for the purpose of decreasing the use of fertilizers, herbicides, and other pesticides by applying chemicals following the principles of Precision Agriculture. Additionally, part of the scope of this dissertation is the development of a control architecture consisting of perception systems, actuation systems, localization systems, and mobile units of differing nature working fully synchronized. This can be accomplished by a communication and location network implementing truly real-time interfaces and real-time control of the perception devices, actuation devices and mobile platforms. This control architecture will rely on artificial intelligence principles to decide what process to apply, where to apply it and the optimum dose. This controller will make decisions as a function of its inputs: perception system data and the history of the mission field.

1.3. Research Objectives

Using the previous approach, this Thesis presents a study in the field of autonomous navigation and control for both vehicles and implements oriented toward Precision Agriculture, and it investigates the most appropriate architectures and methodologies for agricultural environments. Thus, **the main objective of the research is the development of a control architecture (hardware/software) capable of integrating sensorial, actuation and decision-making elements to establish a fully autonomous agricultural system as part of a real fleet of robots, with the primary purpose of performing site-specific weed control tasks and diminishing the use of agricultural inputs**. This control architecture should be characterized by robustness (maintaining high performance under dynamic conditions) and flexibility (easily allowing the addition of new sensory and actuation elements) and support real-time, high-precision work in the actuation task. Additionally, the proposed control architecture is to be integrated and tested in a real fleet of robots featuring the complete autonomy of fleet vehicles capable of traveling at a speed of between 3 and 6 Km/h in crop fields while executing diverse autonomous agricultural tasks (herbicide application, mechanical weed control, etc.).

This architecture was initially evaluated in a simulation environment for fleets of robots applied to agriculture, which has been developed as a part of the research, and was later tested under real-world conditions using a fleet of autonomous robots.

The specific objectives are the following:

1. To study and implement algorithms for crop-row-following by autonomous agricultural vehicles using information from a perception system (consisting of machine vision and a GPS) as the input. The target was to follow the crop rows with an accuracy of approximately ± 2 cm to ensure the safety of the crop.
2. To design, develop and tune a control system for the lateral displacement correction of an implement for physical weed control, allowing errors of less than 0.5 cm. The implement is coupled to the autonomous vehicle using a standard 3-point attachment (3-point hitch), which contains an actuation system that allows the implement to modify its lateral position with respect to the autonomous vehicle. The lateral position of the implement must be modified due to the imperfections of the land and the seeding as well as the displacement of the autonomous vehicle due to corrections in the trajectory. Corrections to the relative position of the implement with respect to the autonomous vehicle must be made to avoid crop damage and to thus ensure effective treatments.
3. To research and develop a control architecture to allow the perception and actuation to be synchronized in real time, in order to achieve a saving of about 75% in agricultural inputs, which is one of the main objectives of the RHEA project.
4. To design, develop and implement a control architecture that will provide the ability to add other elements for the expansion of the initial system, incorporating different communication systems, sensors and actuators, in addition to supporting other types of agricultural implements. To accomplish this, the control architecture should be sufficiently flexible yet robust enough to allow the easy integration of other devices without decreasing its performance.
5. To design, develop and implement the required elements to allow a human operator to remotely control the mobile autonomous unit, maintaining the required safety levels to protect the system and the environment.

6. To design and develop a simulation environment to allow the effect of mobile robots on the execution of Precision Agriculture techniques to be studied and evaluated. This tool will let the designers perform an intermediate step in the validation of the developments arising from this research prior to being implemented in a real agricultural scenario. The simulation environment must provide some capabilities for addressing both agricultural and robotic knowledge through advanced computational tools (MATLAB, Webots) to introduce information in an easy and friendly manner. Additionally, the models required to emulate the operational conditions of a fully autonomous agricultural system must be developed and integrated (autonomous vehicles and implements, field and crop variabilities, etc.).
7. To verify and validate the control architecture and the algorithms developed and implemented in real autonomous agricultural units working in a real agricultural environment.
8. To disseminate the results so that the scientific and technical community involved in autonomous vehicles can take advantage about the progress.

1.4. Contributions

Along with the work performed during the research described in this Thesis, several important contributions have been published in diverse, high-impact journals. The major contributions fall within the area of fleets of autonomous robots oriented toward performing agricultural tasks as well as in the area oriented toward the integration of sensor and actuation systems in autonomous agricultural vehicles, whereby three main publications have been produced. Additionally, six other significant contributions have resulted from the integration and collaboration of a diverse number of universities and research groups, as well as researchers in foreign countries, allowing the work performed here to be part of other significant publications in the areas of computer vision and agricultural engineering. In the following, each contribution is described in detail.

1.4.1. Main Contributions

Robotics applied to agriculture is a very complex field, where a large amount of knowledge from diverse research areas must be combined and integrated to achieve an application that works, is reliable, reaches the farmers and performs the action for which it was designed. One element that enables the integration of new knowledge is the use of simulation tools, which also allows one to perform a prior assessment in the early stages of the design as well as the evaluation of new developments both in robotics and in agriculture.

Based on this premise, one of the main contributions of this Thesis is the development of a simulation environment that attempts to form this bond between robotics and agricultural knowledge, allowing the user to develop new robotics systems and algorithms based on different levels of configurations, depending on which part of the knowledge is to be provided. This computational tool is named "*Simulation Environment for Precision Agriculture Tasks using Robot Fleets*" (SEARFS), and its main objective is to allow the study and evaluation of the execution of agricultural tasks that can be performed by an autonomous fleet of robots. The environment is based on a commercial mobile robot simulation tool that enables the analysis of the performance, cooperation, and interaction of a set of autonomous robots while simulating the execution of specific actions on a three-dimensional (3D) crop field. The environment is capable of simulating new technological advances, such as a GPS, GIS, automatic control, in-field and remote sensing, and mobile computing, which will permit the evaluation of new algorithms derived from Precision Agriculture techniques. This contribution was published in the journal *Industrial Robot*:

Emmi, L., Paredes-Madrid, L., Ribeiro, A., Pajares, G., Gonzalez-de-Santos, P. 2013. Fleets of robots for precision agriculture: A simulation environment. *Industrial Robot*, *40*(1), pp. 41-58.

Chapter 3 presents, in detail, the design, development and implementation of the SEARFS simulation environment.

As presented in the previous subsection, because of recent technological advances that have emerged in the last 20 years, the integration of many autonomous vehicles, particularly agricultural robots, has been facilitated and allows greater accuracy when executing various tasks (Åstrand and Baerveldt, 2002; Bakker et al., 2011; Li et al., 2009; Pedersen et al., 2006; Stentz et al., 2002). Examples of such technological advances are specialized sensors (machine vision, GPS real-time kinematics (RTK), laser-based equipment, and inertial devices), actuators (hydraulic cylinders and linear and rotational electrical motors), and electronic equipment (embedded computers, industrial PCs, and PLCs). However, most of the robotics applications oriented toward the execution of agricultural tasks, which can be found both in the scientific literature as well as in commercial products, focus on solving a specific problem, e.g., autonomous guidance or autonomous crop operation (Auat Cheein et al., 2013; Bakker et al., 2010a; Blackmore et al., 2001; Fountas et al., 2007; Katupitiya et al., 2007; Rovira-Más, 2010a), and only few attempts to establish a fully autonomous agricultural system have been proposed (Bergerman et al., 2012; Blackmore et al., 2004; Johnson et al., 2009; Kohanbash et al., 2012; Moorehead et al., 2012; Nørremark et al., 2008; Pilarski et al., 2002). Another important contribution derived from the research is the proposal of a hardware architecture capable of integrating different sensor and actuation systems developed by diverse research groups as well as different types of commercial equipment with the objective of structuring and integrating a fully autonomous agricultural system as a part of a fleet of robots.

To achieve the structure of the proposed architecture, an analysis of the requirements of a fully autonomous agricultural system was made in addition to an analysis of the requirements of such autonomous systems working together in a fleet of robots. The proposed architecture was designed to be flexible and capable of integrating several standard communication protocols that are common in high-tech agricultural applications. Additionally, another requirement of the proposed architecture was modularity, i.e., providing convenient settings of the interfaces between the sensors and devices and the proper organization of the perception, processing, and actuation of these types of systems due to the large variety of available technologies. This contribution was published in the journal *The Scientific World Journal*:

Emmi, L., Gonzalez-de-Soto, M., Pajares, G., Gonzalez-de-Santos, P. 2014. New Trends in Robotics for Agriculture: Integration and Assessment of a Real Fleet of Robots. *The Scientific World Journal*, *2014*, pp. 1-21.

Chapter 4 presents, in detail, the design and development of a system architecture for both individual robots and robots working in fleets to improve reliability, decrease complexity and costs, and allow the integration of software from different developers.

Extending the idea of implementing and integrating a fully autonomous agricultural system, and using the proposed architecture as a base, the third main contribution of the investigation is a configuration of a complete system, integrating perception, actuation, and decision making as subsystems for an agricultural autonomous system working on real wide-row crops. This is performed by the selection, arrangement, integration, and synchronization of the perception, actuation, and decision-making subsystems, which provides a model for a complete autonomous vehicle for agricultural applications to be structured and tested. The experimental results derived from this contribution demonstrate the success and performance of the integrated system in guidance and weed control tasks in a maize field, indicating its utility and efficiency.

The integration developed in this study was intended to allow the various systems that constitute the autonomous vehicle to work together by synchronizing the information from the perception system (machine vision, RTK-GPS and IMU) using a specialized actuation system (site-specific weed control for maize crops) as well as the guidance of the vehicle itself. The results obtained in this study allow the fully autonomous agricultural system to be parameterized and its capabilities and limitations to be defined. In addition, the precision and associated delays of both the vision and actuation systems were measured, allowing the evaluation of the ability of the entire agricultural system to perform an effective treatment, i.e., how much of the product can be saved, which is the ultimate objective of Precision Agriculture. This contribution was published in the journal *Sensors*:

Emmi, L., Gonzalez-de-Soto, M., Pajares, G., Gonzalez-de-Santos, P. 2014. Integrating sensory/actuation systems in agricultural vehicles. *Sensors*, *14*, pp. 4014-4049.

Chapter 5 presents, in detail, the selection, arrangement, integration, and synchronization of the elements that compose the sensory as well as the actuation system for a fully autonomous agricultural system.

1.4.2. Other Contributions

In addition to the main contributions listed in the previous section, the work developed has also generated other contributions from work performed in cooperation with other research centers and universities.

Given that the developments contain significant elements of integration between sensory and actuation systems, a substantial amount of work was performed with the ISCAR research group, which is under the Faculty of Informatics, University Complutense of Madrid (UCM). This work, which represents major contributions but in cooperation with other partners, allowed the execution of diverse field tests with an agricultural autonomous vehicle to make adjustments to and to validate the assemblies and algorithms developed by the UCM partners. In these works, the main elements of the architecture presented in (Emmi et al., 2014a; Emmi and Gonzalez-de-Santos, 2012), which are related to the acquisition, synchronization, and execution of image processing algorithms, where applied. The integration of these algorithms as modules into the proposed architecture to perform in real time constitutes another important contribution of this research. These contributions where published in the journals *Sensors* and *Expert Systems with Applications* as part of the complete systems, where the integration issues are described in Chapters 4 and 5.

Romeo, J., Guerrero, J.M., Montalvo, M., Emmi, L., Guijarro, M., Gonzalez-de-Santos, P., Pajares, G. 2013. Camera Sensor Arrangement for Crop/Weed Detection Accuracy in Agronomic Images. *Sensors*, *13*, pp. 4348-4366.

Guerrero, J.M., Guijarro, M, Montalvo, M., Romeo, J., Emmi, L., Ribeiro, A., Pajares, G. 2013. Automatic expert system based on images for accuracy crop row detection in maize fields. *Expert Systems with Applications*, *40*(2), pp. 656-664.

Montalvo, M., Guerrero, J.M., Romeo, J., Emmi, L., Guijarro, M, Pajares, G. 2013. Automatic expert system for weeds/crops identification in images from maize fields. *Expert Systems with Applications*, *40*(1). pp. 75-82.

Other contribution also derived from the work in cooperation with another RHEA project partner was the evaluation of the use of diverse satellite-based localization solutions for autonomous guidance of vehicles developed for agricultural applications. This assessment was performed by using the control architecture developed in this thesis, deriving a publication in the journal *Applied Engineering in Agriculture*:

Carballido, J., Perez-Ruiz, M., Emmi, L., Agüera, J. 2014. Comparison of Positional Accuracy between RTK and RTX GNSS Based on the Autonomous Agricultural Vehicles under Field Conditions. *Applied Engineering in Agriculture*, *30*, pp. 361–366.

In addition to these major contributions, which were made in cooperation with other partners, other contributions have arisen from the research. One of these contributions, published in the *First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, presents a lateral positioning controller for agricultural vehicles based on fuzzy logic and on the procedure to integrate new knowledge, especially for controllers, in the SEARFS simulation environment:

Emmi, L., Pajares, G., Gonzalez-de-Santos, P. 2012. Integrating robot positioning controllers in the SEARFS simulation environment. In *Proceedings of the First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, Pisa, Italy, 19-21 September, 2012, pp. 151-156.

Another contribution, submitted to the same RHEA conference, presents a first approach of the control architecture subsequently published in (Emmi et al., 2014a):

Emmi, L., Gonzalez-de-Santos, P. 2012. Hardware architecture design for navigation and precision control in autonomous agricultural vehicles. In *Proceedings of the First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, Pisa, Italy, 19-21 September, 2012, pp. 217-222.

Additionally, other contribution also submitted to the RHEA conference, presents the use of some elements of the SEARFS simulation environment for analyzing the dependency of the accuracy of the green density detection of crop and weeds based on the variations in the camera pitch angle:

Guerrero, J.M., Romeo, J., Emmi, L., Montalvo, M., Guijarro, M, Pajares, G., Gonzalez-de-Santos, P. 2012. Influence of the vision system pitch angle on crop and weeds detection accuracy. In *Proceedings of the First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, Pisa, Italy, 19-21 September, 2012, pp. 319-324.

Furthermore, this work allowed the realization of a research stay at the University of Pisa, producing a contribution to the design of a mechanical-thermal implement for weed control, which was used in this thesis to validate the integration of a perception system with that actuation system using the control architecture presented. This contribution was published in the *Second International Conference on Robotics and associated High-technologies and Equipment for Agriculture and forestry*:

Frasconi, C., Martelloni, L., Fontanelli, M., Raffaelli, M., Emmi, L., Pirchio, M., Peruzzi, A. 2014. "Design and full realization of physical weed control (PWC) automated machine within the RHEA project". In *Proceedings of the Second International Conference on Robotics and associated High-technologies and Equipment for Agriculture and forestry (RHEA-2014)*. Madrid, Spain, 21-23 May, 2014, pp. 3-12.

Finally, some publications were also published in several international conferences where the main idea of the RHEA project was presented:

Peruzzi, A., Raffaelli, M., Emmi, L., Fontanelli, M., Frasconi, C., Gonzalez-de-Santos, P. 2011. "The Rhea Project: a fleet of autonomous robot able to perform physical weed control in herbaceous and vegetable crops". In *Proceedings of the V International Scientific Symposium "Farm Machinery and Process Management in Sustainable Agriculture"*- Lublin, Poland, 23-24 November 2011, pp. 119-122.

Peruzzi, A., Vieri, M., Emmi, L., Raffaelli, M., Fontanelli, M., Rimediotti, M., Frasconi, C., Sarri, D., Lisci, R., Gonzalez-de-Santos, P. 2011. "Il progetto RHEA: definizione e gestione delle attrezzature per il controllo fisico delle infestanti da implementare su una flotta di robot autonomi". In *Proceedings of the Convegno Nazionale A.I.I.A. – Gestione e controllo dei sistemi agrari e forestali,* Belgirate, Italy, 22-24 Settembre 2011, pp. 7.

Gonzalez-de-Santos, P., Vieri, M., Ribeiro, A., Raffaelli, M., Emmi, L., Fontanelli, M., Rimediotti, M., Frasconi, C., Sarri, D., Peruzzi, A. 2011. "Il progetto RHEA: una flotta di robot autonomi per la gestione mirata del controllo chimico e non chimico delle infestanti su specie erbacee di pieno campo e dei trattamenti alle colture arboree". In *Proceedings of the Convegno Nazionale A.I.I.A. – Gestione e controllo dei sistemi agrari e forestali*, Belgirate, Italy , 22-24 Settembre 2011, memoria 62, pp. 6.

1.5. Outline of the Thesis

To develop the specific objectives presented above, this dissertation is organized into six chapters that follow a specific research line. This current chapter briefly presented the problem to be solved as well as the contributions and objectives proposed.

Chapter 2 represents the starting point. It presents the state of the art of fully autonomous agricultural systems and general framework for solving the navigation and control problem of this type of mobile robot in addition to a short analysis of the use of simulation tools in both robotics and in agriculture.

Chapter 3 presents the development of a simulation environment that allows the execution of agricultural tasks by a fleet of robots to be observed and evaluated. It is the natural step prior to the real-world developments. This chapter also presents two interfaces that constitute this simulation environment: a configuration interface and a graphical interface, which interact with each other. These interfaces allow the crop field, the fleet of robots and the different sensors and actuators that are incorporated into each robot to be configured. In addition, an evaluation of the simulation environment is presented in this chapter, where a mission that simulates a weed control task in a field (through advanced recognition and decision-making techniques using a fleet of robots) has been designed and implemented.

Chapter 4 presents the development of a system architecture for both individual robots and robots working in fleets to improve reliability, decrease complexity and costs, and permit the integration of software from different developers. It is the step prior to integration. In this chapter, several solutions are studied, from a fully distributed system, in which every subsystem is controlled by an independent computer, to a fully integrated architecture, in which a central computer runs all the processes. Moreover, this chapter also studies diverse topologies for controlling fleets of robots and advances other prospective topologies for applications when legislation on mobile robotics permits the use of autonomous systems not supervised by humans in real-world applications. The architecture presented in this chapter is being successfully applied in the RHEA fleet, which comprises three ground mobile units based on a commercial tractor chassis.

Chapter 5 presents the selection, arrangement, integration, and synchronization of the diverse elements that constitute an autonomous vehicle for agricultural applications. It describes the complete system assessment and validation. In this chapter, the experimental results are also presented, which demonstrate the success and performance of the integrated system in guidance and weed control tasks in a maize field, demonstrating its utility and efficiency. The integration devised in this chapter produces a fully autonomous agricultural system sufficiently flexible for use in other agricultural tasks using little effort, which is another important contribution in the field of autonomous agricultural vehicles.

Finally, Chapter 6 summarizes the main conclusions of this Thesis as well as presents an outline of future work.

Chapter 2

Autonomous Systems in Precision Agriculture: revision and frameworks

2.1. Introduction

As mentioned before, Precision Agriculture is known as the set of methodologies that aim to optimize agricultural field management focusing on the enhancement of crop knowledge, environmental protection and economics. Precision Agriculture is a management concept that relies on observing and responding to field variations by using modern technologies, such as Global Positioning Systems, Geographic Information Systems, microcomputers, automatic control, in-field and remote sensing, mobile computing, advanced information processing, telecommunications and robotics (See Figure 2.1). All these techniques offer great benefits for applying the management principles to in-field unpredictability of soil and crop such as yield variability (historical and present yield distributions), field variability (field topography), soil variability (e.g. soil fertility, physical soil properties), crop variability (e.g. crop density, height, nutrients and water stress), management variability (tillage practices, crop seeding rates, crop rotations, fertilizer applications, pesticide applications, irrigation patterns), etc. (Zhang et al., 2002).

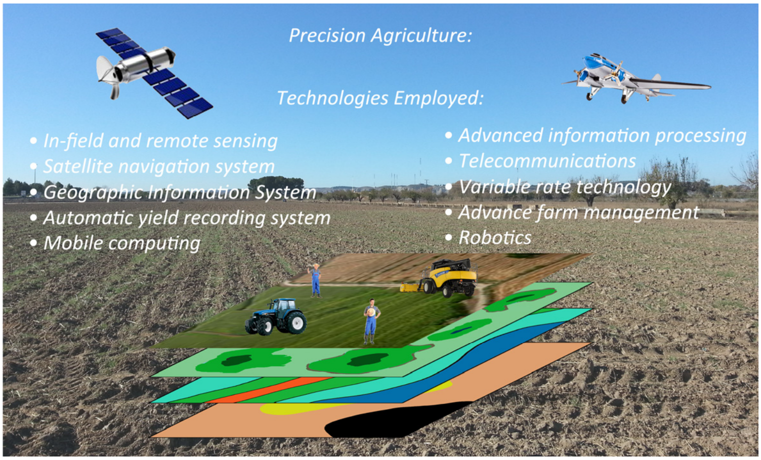


Figure 2.1. General schema of diverse technologies that are employed in Precision Agriculture tasks.

To manage the unpredictability/variability within a field and because of new advances in sensors (machine vision, RTK-GPS, laser-based equipment, and IMU), actuators (hydraulic cylinder, linear and rotational electrical motors) and electronic equipment (embedded computers, industrial PC, PLC) over the past two decades, multiple research trends have arisen from the idea of developing agricultural robots to cultivate, harvest, and control diseases (Åstrand et al., 2002; Bakker et al., 2011; Li et al., 2009; Pedersen et al., 2006; Stentz et al., 2002). These autonomous/semi-autonomous systems provide accurate positioning and guidance in the working field, which makes them capable of conducting Precision Agriculture tasks if equipped with the proper implements (agricultural tools or utensils). Those implements (variable application rates of fertilizers or sprays, mechanical intra-row weed control, seed planters) are also being automated with the same types of sensors and actuators used in autonomous vehicles (GPS, machine vision, range finders, etc.) (Gan-Mor et al., 2007; Nieuwenhuizen et al., 2010; Pérez-Ruiz et al., 2012; Slaughter et al., 2008; Tian, 2002; Tillett et al., 2008).

Some authors agree that, in general terms, the framework of an agricultural autonomous guidance system mainly consist of four subtasks: sensor acquisition, modeling, planning, and execution (Li et al., 2009; Reid et al., 2000). Based on this generalization, Figure 2.2 presents a simplified framework for agricultural guidance in which the outputs of each subtask are highlighted. Following this framework, and based on a review of the research activities in autonomous crop operations over the

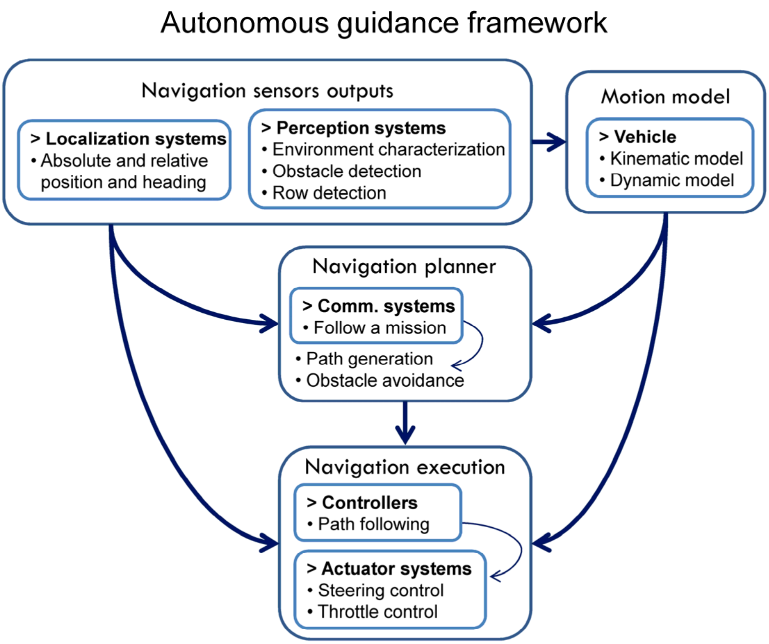


Figure 2.2.General framework of guidance system for agricultural vehicles.

last fifteen years, we can construct an analogy and present a general framework of agricultural autonomous implements (See Figure 2.3).

For each framework, we can identify some similarities in (a) the usage of sensors and actuators, (b) the flow data general scheme, and (c) the specific subtask that uses the sensors and actuators. For example, the use of machine vision in both frameworks is commonly applied for crop row detection to localize and adjust the relative position of the vehicle/implement depending on the environment; the use of the GPS in both frameworks is commonly applied for absolute localization to follow a predefined route or for the application of a specific treatment in a specific location.

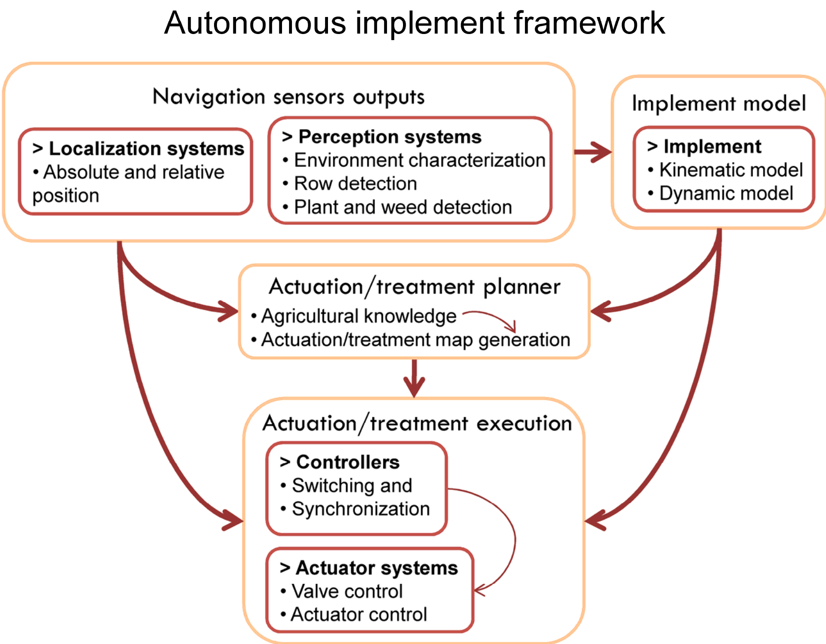


Figure 2.3. General frameworks of control system for autonomous implements.

2.1. Fully Autonomous Agricultural Systems: First Step Towards Precision Agriculture

Apart from the problems of making a vehicle autonomous, an agricultural system needs to be equipped with the proper implements to carry out farming tasks such as tilling, seeding, weed control, fertilizing, applying pesticide, mowing, and harvesting. This is a step forward in the automation of agricultural systems, defined in the previous chapter as fully autonomous agricultural system, which is one of the areas that this Thesis is focused on.

In fully autonomous agricultural systems, several actions must be executed simultaneously to ensure effective application as well as safety (including the system, the crop field, and external elements, e.g. human supervisors). Absolute or relative localization in the field, obstacle and interesting element detection, communication with external users or with other autonomous units, autonomous navigation or remote operation, and site-specific applications are some of these specific actions that, all together, compose a fully autonomous agricultural system. This system can be divided into two main subsystems (See Figure 2.4): the autonomous vehicle and the autonomous implement. The autonomous vehicle, such as a modified commercial tractor, specialized mobile platform or small vehicle, guides the agricultural system in a crop field for the purpose of executing a crop operation (e.g., harvesting, hoeing, weed control), which will be accomplished by the autonomous implement. Given the complexity of the assignment, a large number of specialized sensors and actuators is required to fulfill the given task in the given environment.

For each individual system presented in Figure 2.4, intensive research activities have been documented in the literature that intend to solve both the autonomous guidance problem and the autonomous crop operation problem individually. Table 2.1 presents selected examples of efforts to solve the autonomous guidance problem, and Table 2.2 presents some works focused on solving the autonomous crop operation problem, indicating the application for which they were developed and the

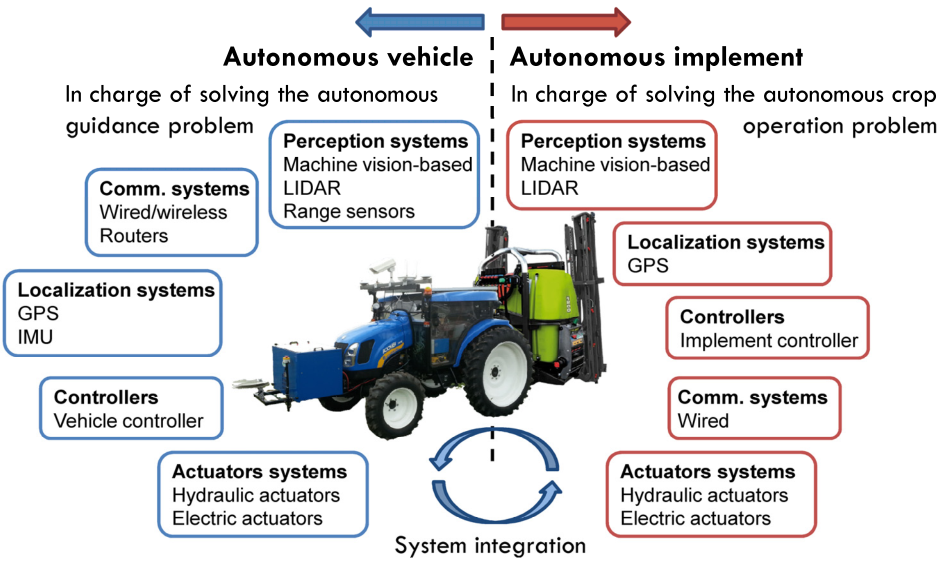


Figure 2.4. Main systems comprising a current autonomous agricultural application and some examples of sensor and actuation systems normally found in this type of application.

main sensor system used. Additionally, Table 2.3 presents a few examples of the activity carried out in developing manipulators for agriculture as well as the use of manipulators for the specific task of weed control, which have promoted the application of Precision Agriculture techniques in many different tasks.

Table 2.1. Examples of autonomous vehicles for agricultural applications developed around the world.

Author / Centre	Blackmore et al. (2004). Dept. of Agricultural Sciences, Frederiksberg, Denmark.
Application	Automatic steered tractor capable of following a predefined route plan.
Sensorial System	RTK GPS: Localization.
Results	The automatic steered tractor can follow a predetermined route within a few centimeters.
Author / Centre	Cho and Lee (2000). Department of Agricultural Engineering, Seoul National University, Korea.
Application	Autonomous operation of a speedsprayer in an orchard (a speedsprayer is defined as a power sprayer used to apply a highly concentrated pesticide in highly dispersed form by delivering it into a strong air blast generated by fans or blowers - Merriam-Webster Dictionary).
Sensorial System	DGPS for Localization; ultrasonic sensor for obstacle detection
Results	Speedsprayer autonomous operation: within 50 cm deviation. The speedsprayer could avoid trees or obstacles in emergency situations.
Author / Centre	Hague et al. (2000). Silsoe Research Institute, Wrest Park, UK.
Application	Ground-based sensing methods for vehicle-position fixing
Sensorial System	Sensor package: machine vision, odometers, accelerometers, and a compass
Results	Reducing the low noise level of the odometric data and eliminating drift using sensor fusion
Author / Centre	Subramanian et al. (2006). Department of Agricultural and Biological Engineering, University of Florida, USA.
Application	Autonomous guidance system for use in a citrus grove
Sensorial System	Machine vision and laser radar (LADAR)
Results	Machine-vision guidance: average error of 2.8 cm. LADAR guidance: average error of 2.5 cm (Tested in a curved path at a speed of 3.1 m/s)
Author / Centre	Xue et al. (2012). Department of Agricultural and Biological Engineering, University of Illinois, USA.
Application	Variable field-of-view machine-vision method for agricultural robot navigation between rows in cornfields
Sensorial System	Machine vision with pitch and yaw motion control
Results	Maximum guidance error of 15.8 mm and stable navigational behavior

Table 2.2. Examples of autonomous implements for agricultural applications developed around the world.

Author / Centre	Blasco et al. (2002). Instituto Valenciano de Investigaciones Agrarias (IVIA), Spain.
Application	Non-chemical weed controller for vegetable crops
Sensorial System	Two machine-vision systems: one in front of the robot for weed detection; the other for correcting inertial perturbations.
Results	The system was able to eliminate 100 % of small weeds. The system properly located 84 % of weeds and 99 % of lettuces.
Author / Centre	Lee et al. (1999). Biological and Agricultural Engineering, University of California, USA.
Application	Real-time intelligent robotic weed control system for selective herbicide application to in-row weeds.
Sensorial System	Two machine-vision systems: one in front of the robot for guidance; the other for weed detection
Results	24.2 % of the tomatoes were incorrectly identified and sprayed, and 52.4 % of the weeds were not sprayed.
Author / Centre	Leemans and Destain (2007). Gembloux Agricultural University, Belgium.
Application	Positioning seed drills relative to the previous lines while sowing
Sensorial System	Machine vision for guidance
Results	The standard deviation of the error was 23 mm, with a range of less than 100 mm.
Author / Centre	Pérez-Ruiz et al. (2012). University of California, Davis, Department of Biological and Agricultural Engineering, USA.
Application	Automatic mechanical intra-row weed control for transplanted row crops
Sensorial System	RTK-GPS for controlling the path of a pair of intra-row weed knives
Results	A mean error of 0.8 cm in centering the actual uncultivated close-to-crop zone about the tomato main stems, with standard deviations of 1.75 and 3.28 cm at speeds of 0.8 and 1.6 km/h, respectively

Table 2.3. Examples of manipulators in Precision Agriculture applications.

Manipulator Task	Description
Melon harvester	Agricultural Cartesian robot focused on the design of the parameters of a robotic melon harvester. Dept of Ind. Eng. & Mgmt. Ben-Gurion Uni. of the Negev, Beer-Sheva, Israel (Edan and Miles, 1994).
Greenhouse manipulator	Robotic arm to evaluate precision spraying for cyclamens and precision fertilization that operates in a fixed position in a greenhouse. DAUIN (Politecnico di Torino), IMAMOTER and DEIAFA (Università degli Studi di Torino), Italy (Belforte et al., 2006).
Harvesting manipulator	Manipulator that can be used for autonomous cucumber harvesting in greenhouses. Farm Technology Group, Wageningen University, the Netherlands (Van Henten et al., 2009).
Weed manipulator	Robotic arm carried by a mobile platform which is trailed by a conventional tractor that eliminates the weeds using electrical discharges. Instituto Valenciano de Investigaciones Agrarias (IVIA), Spain (Blasco et al., 2002).
Patch sprayer	Manipulator for a target-oriented weed control system through the integration of differential GPS (DGPS), GIS, and solenoid-activated spray nozzles. Department of Agricultural Machinery, College of Agriculture, Shiraz University, Shiraz, Iran (Loghavi and Mackvandi, 2008).

A few attempts to establish a fully autonomous agricultural system by integrating an autonomous vehicle and an autonomous implement can be found in the scientific literature. One of the most important examples is the work conducted in Denmark by Nørremark et al. (2008). These authors developed a self-propelled and unmanned hoeing system for intra-row weed control comprising an autonomous tractor (Blackmore et al., 2004) and a cycloid hoe (Wisserodt et al., 1999) linked via a hydraulic side-shifting frame attached to the rear three-point hitch of the tractor. In this system, the autonomous tractor follows a predefined route parallel to the crop rows and turns at the end of the rows, the side-shift frame adjusts its lateral position depending on predefined waypoints, and the cycloid hoe controls the tines to avoid contact with crop plants. Both the vehicle and the implement are controlled independently according to a predefined mission. However, some sensorial systems are replicated; for example, there is one GPS for the vehicle guidance and another for the side-shifting and cycloid hoe control systems.

2.2. Fleet of Robots: Second Step Towards Precision Agriculture

Many research groups are developing specialized autonomous applications for agriculture that will be operative in the coming years (Bakker et al., 2010b; Nagasaka et al., 2009; Nørremark et al., 2008), but many others are also aiming to operate a group of vehicles under unified control. This is the emergent concept of fleets of robots, which represents a step forward in automation of agricultural activities: the use of carrier platforms and mobile robots to perform various tasks simultaneously. The associated theoretical foundations of fleets of robots have been investigated recently (Bautin et al., 2011; Bouraqadi et al., 2012), but the first applications for agriculture are currently under development. This scenario is the case of two projects funded under the Seventh Framework Program: *RHEA - Robot Fleets for Highly Effective Agriculture and Forestry Management* (RHEA, 2014) and *CROPS - Intelligent sensing and manipulation for sustainable production and harvesting of high value crops* (CROPS, 2014). The RHEA project, on which the research is inspired, focuses on the design, development, and testing of a new generation of automatic and robotic systems for both chemical and physical effective weed management, applicable to both agriculture and forestry. In contrast, the CROPS project focuses on the development of scientific know-how for a highly configurable, modular, and clever carrier platform that includes modular parallel manipulators and intelligent tools (sensors, algorithms, sprayers, grippers), which can be easily installed onto the carrier and are capable of adapting to new tasks and conditions.

The aforementioned projects have in common the use of advance perception systems and innovative actuation systems on board mobile platforms with different degrees of autonomy. Small vehicles ensure higher positioning accuracy during operation and are intrinsically lighter than big machines. This last feature reduces the soil compaction and makes the vehicles safer in terms of safety to others, own safety and crop safety, all important features in agricultural equipment nowadays (Blackmore et al., 2001). However, small robots manage smaller implements and payloads than big machines do. We therefore need several small robots to accomplish tasks which are similar to what a big machine can manage. This raises the concept of fleets of robots with additional advantages regarding price (it allows farmers to get high-technology equipment in an increasing manner), fault tolerance (failure in a small robot means one less robot at work, while failure in a big vehicle means the whole process on the field is stopped), mission coordination and reconfiguration (at any time we can change the fleet behavior to optimize the mission, taking into account sudden changes in field conditions), etc. For this purpose, the concept of reducing redundant devices coordinating different, heterogeneous systems by using a central, external computer is prominent.

Fleets of robots can provide many advantages (Blackmore et al., 2005; Cheung et al., 2008; Peleg, 2005; Sørensen and Bochtis, 2010): using a group of robots cooperating with each other to achieve a well-defined objective is an emerging and necessary concept to achieve the application of autonomous systems in daily agricultural tasks. The implementation of complex and expensive systems will be attractive for high-value crops for which smart machines can replace extensive and expensive repetitive labor. However, for a robotic agricultural application, considerable information must be processed, and a wide number of actuation signals must be controlled, which may present a number of technical drawbacks. Thus, an important limitation is that the number of total devices (e.g., sensors, actuators, computers/controllers) increases according to the number of fleet units, and thus the mean time between failures decreases drastically because a failure in one robot component causes the entire fleet to be out of order. This decrease in the time between failures significantly influences fleet reliability, which is of paramount importance for the application of automated systems to real tasks and, in particular, to agriculture.

To achieve a flexible, reliable, and maintainable fleet of autonomous mobile robots for agricultural tasks, the system architecture (involving sensors, actuators, and the computers performing the algorithms) for both the vehicle navigation system and the operation of the implement must be robust, simple, and modular. One of the most important tasks in a control configuration design is the selection of the number and type of sensors, actuators, and computers. These components constitute the basis for the design of the architecture and are very difficult to decrease in number because the processes of perceiving and actuating cannot be avoided; however, these sensors and actuators are typically handled by independent controllers, specifically, commercial off-the-shelf (COTS) sensors such as LIDARs, vision systems and so on. However, computers are sufficiently flexible to share resources and improve the robustness of the system.

2.3. Design of Fleets of Robots for Precision Agriculture

2.3.1. Analyzing Fleets of Robots: Simulation Tools

The work presented in this Thesis was derived from the RHEA consortium's need to evaluate features of different fleet of robots configurations in advance, i.e. before developing and manufacturing the mobile units. This problem is traditionally being alleviated through many research activities by computer simulation. Simulating sensors, actuators, manipulators and mobile robots in general can be developed by using commercial software applications (See Table 2.4). However, they rely on geometric, kinematic and dynamic simulations and do not take into account other external factors such as different agricultural features needed to perform simulations with a certain degree of pragmatism (e.g. crop and weed spatial distribution models, soil physical characteristic models, and terrain slope models).

Table 2.4. Several robot simulation tools used up today.

Simulator	Description
Gazebo	3D multi-robot simulator with dynamics, capable of simulating articulated robots in complex and realistic environments (Vaughan et al., 2003).
Simbad	Java 3D robot simulator for studying situated artificial intelligence, machine learning (AI algorithms), in the context of Autonomous Robotics and Autonomous Agents (Hugues and Bredeche, 2006).
Microsoft Robotics Developer Studio	Visual Simulation Environment that enables users to develop robots in a rich virtual environment with realistic physics and state-of-the-art rendering (Johns and Taylor, 2008).
Robot studio, ROS	Open-source, meta-operating system for robots. Provides services such as hardware abstraction, low-level device control, implementation of commonly used functionality, message-passing between processes, and package management (ROS, 2014).
Webots	Development environment used to model, program and simulate mobile robots. The user can design complex robotic setups, with one or several similar or different robots, in a shared environment (Cyberbotics, 2014).

Agricultural simulation applications also exist, such as those illustrated in Table 2.5. These are quite interesting to study in terms of the effects of climate, soil, cultivar types and management in the potential growth of a crop and the agricultural production, but fail when interacting with vehicles and robots.

Table 2.5. Example of simulation tools used in Precision Agriculture applications.

Simulator	Description
Agriculture Production Systems Simulator (APSIM),	APSIM is a tool for exploring agronomic adaptations such as changes in planting dates, cultivar types, and fertilizer/irrigation management (Keating et al., 2003).
Cropping Systems Simulation Model (CropSys),	CropSys is a system that is used as an analytical tool to study the effects of climate, soil, and management in agricultural production systems and the environment (Stöckle et al., 2003).
The Decision Support System for Agrotechnology Transfer (DSSAT)	A software package that combines the effects of soil, crop phenotype, weather and management options which allow the user to get results by conducting simulation experiments (Thorp et al., 2008).
Simple and Universal Crop Growth Simulator (SUCROS)	SUCROS is a mechanistic model that explains crop growth on the basis of the underlying processes. It simulates potential growth of a crop and can also describe production under water-limited conditions by including water balances of crop and soil (Goudriaan and Van Laar, 1994).

2.3.2. Integrating Control Architectures

Autonomous outdoor navigation of vehicles with integrated sensor and actuation systems was proposed in the 1920s, but it was first realized in the 1980s, when the technology was mature enough to allow for actual tests (Li et al., 2009). Currently, there exists a growing interest in the field with significant progress (Auat Cheein et al., 2013). NavLab was one of the first and more outstanding vehicles capable of navigating in a real, dynamic environment with the help of machine vision, a range finder and heavy computing power onboard the vehicle (Hebert, 1986). A few years later, some researchers tried to automate agricultural vehicles by using different concepts and techniques. Erbach et al. (1991) proposed a static system based on radio beacons to triangulate the vehicle's position for steering purposes. A similar system using cameras in the field to track a visual mark on the vehicle was also used to determine the position of the tractor (Noguchi et al., 1997). Although this system was successful, researchers returned to the NavLab philosophy by putting cameras onboard the vehicle. The static vision system evolved toward mobile equipment that was able to identify the environment and use its features for vehicle steering purposes. This technique led several researchers (Billingsley and Schoenfisch, 1995; Gerrish et al., 1997) to develop controllers for autonomous agricultural tractors to track straight crop rows.

A different approach, based on GPS, was proposed by O'Connor et al. (1996) at around the same time. These authors demonstrated how an autonomous vehicle equipped with a carrier phase GPS with four antennas can provide both position and heading in the field with accuracy high enough to accomplish agricultural tasks. Since then, GPS has been adopted as the typical technique for measuring and controlling a vehicle's position and heading, and it has been included in some commercial systems (Rekow and Ohlemeyer, 2007). Nevertheless, research is still ongoing, and new approaches using GPS for the autonomous guidance of tractors have recently been proposed (Gomez-Gil et al., 2011).

Although GPS technology provides good accuracy for guiding agricultural vehicles, machine vision has been shown to be crucial to identify environmental particularities and obstacles; therefore, both techniques started to be merged in the 2000s and became the standard approach for agricultural vehicles (Stentz et al., 2002). Specifically, camera-based systems have been developed for guidance as the main task (Kise and Zhang, 2008; Rovira-Más et al., 2003) and for weed and crop discrimination, where guidance was a consequence (Gée et al., 2008; Guerrero et al., 2013; Jones et al., 2009; Montalvo et al., 2012; Romeo et al., 2013; Zheng et al., 2009). Guidance and detection tasks require sensors and elements to be conveniently arranged, adjusted, and calibrated onboard the vehicle for accuracy during implementation (Rovira-Más et al., 2011; Xue et al., 2012).

One important concern in agriculture is productivity, where agricultural tasks have to be carried out with accuracy, maximum performance, and minimal resources. This situation means that the integration of the aforementioned systems (the vehicle and the implement) must be carried out under an architecture with an effective and reliable design to meet all requirements, specifically the expected real-time. Thus, the architecture is a crucial issue, where all subsystems are to be coordinated. Suprem et al. (2013) highlighted the importance of the effective integration of sensors, computers, and actuators. There has been a great emphasis on the development of the individual elements but not so much on their integration; note that integration is particularly crucial in agricultural vehicles where the ideal situation is to design flexible and open systems for more than one agricultural application, as mentioned by (Blackmore et al., 2005), with the aim of making full use of agricultural vehicles for a wide range of agricultural applications. Accordingly, García-Pérez et al. (2008) proposed a hybrid agent-based architecture for agricultural purposes, where perception and actuation tasks are integrated and conveniently coordinated.

Slaughter et al. (2008) reviewed systems in autonomous robots for agricultural tasks and identified four main subsystems: guidance, weed detection and identification, precision actuation, and mapping. Guidance and weed detection and identification are based on RTK-GPS and imaging sensors. Actuation systems are focused on precise control where weeding is a specific agricultural treatment (Pedersen et al., 2006), based on micro-sprays, cutting tools or thermal and electrocution devices. Mapping is the process of applying information obtained at a previous stage to the application; Bak and Jakobsen (2004) obtained a map during sowing, which was used during the treatment of weeds. These four subsystems are also described in (Auat Cheein et al., 2013).

On the other hand, Rovira-Más (2010a, 2010b) proposed an open architecture for intelligent autonomous vehicles, based on a three-layer (safety, information and machine actuation) structure. The safety layer is responsible for all security aspects concerning the vehicle and the user's integrity. The information layer (perception) is in charge of processing all data supplied by the set of sensors onboard the tractor. Finally, the actuation layer (action and decision making) executes the decisions made according to the intelligent processes. All of these layers are interrelated to fulfill the difficult agricultural requirements. It is clear that, for the progress of agricultural autonomous vehicles, it is necessary to follow an architectural model based on such schemes with the required flexibility and scalability to expand the range of the vehicle's applications while simultaneously achieving adequate robustness and efficiency. Rovira-Más (2010a) developed the perception system in depth, emphasizing the sensor deployment under a specific configuration for real-time purposes, as well as analyzing the following four important properties: flexibility, scalability, robustness, and efficiency.

Based on the above considerations, we propose an architecture that integrates the above four subsystems (guidance, weed detection and identification, precision actuation, and mapping) while covering the above-mentioned four properties (flexibility, scalability, robustness, and efficiency). This process is achieved with the proposed scheme displayed in Figure 2.5. It consists of three main modules: sensing, acting, and decision making. Sensing is in charge of collecting information from the environment through the set of sensors available (imaging, inertial systems, and GPS). The information must be appropriate for guidance, weed/crop detection and identification, and mapping. Sensors are adapted according to tasks to be carried out, and new sensors could be added when required, such as range finders for safety navigation (flexibility). Depending on the agricultural application, each sensor can

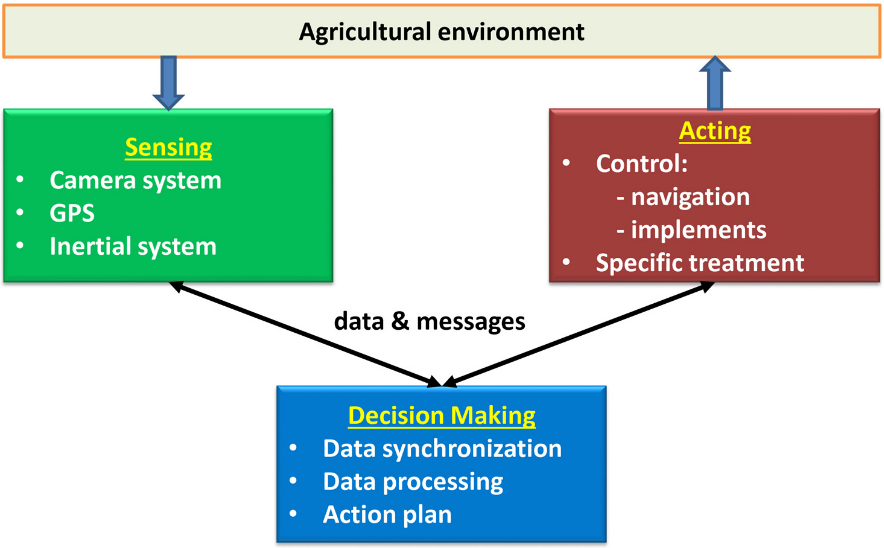


Figure 2.5. Architectural design: perception (sensing), actuation, and decision making.

be replaced by similar sensors with different specifications (scalability). The harsh environmental conditions must be determined by sensors (robustness). All sensors must be able to provide data to be synchronized for real-time implementation (efficiency). The decision-making system is in charge of processing the information through specific procedures and algorithms for guidance, weed detection and identification, and mapping. The hardware/software components are designed with the aim of receiving all available information supplied by the sensors, which can be activated/deactivated conveniently (flexibility, scalability). These components control all data and processes to guarantee that they are received on time (robustness) with the required coherence for real-time applications (efficiency). After this, decisions are made to be transmitted (messages) to the perception and/or actuation systems when required. Control actions are applied either for navigation or on the agricultural implements for specific tasks, such as weeding. Different implements should be possible, and different parts of the implements can be activated or deactivated (flexibility and scalability). Implements must act with the highest precision as possible for site-specific applications (robustness and efficiency). All subsystems are linked with the appropriate communication protocol.

2.4. Discussion and Conclusion

In the last two decades a huge amount of developments derived from important research works, and aided by recent technological advances in computer vision and localization, has allowed Precision Agriculture techniques to be implemented efficiently. These research works have helped to develop autonomous vehicles for several agricultural applications as well as autonomous implements, especially for weed control tasks. Thanks to this, the concepts of fully autonomous agricultural systems as well as the use of fleet of robots in agricultural tasks have been growing so far, where the integration of these new technological advances in Precision Agriculture is required. Some authors have proposed diverse theoretical approaches to achieve such integration by developing control architectures and frameworks, but there are still several steps to meet to bring a fully autonomous agricultural system into industry. One of the first steps would consist of taking these concepts into practice by integrating a fully autonomous agricultural system and evaluating its performance in real agricultural applications.

Chapter 3

Simulation Environment for the Evaluation of Precision Agriculture Techniques with Autonomous Vehicles

3.1. Introduction

In order to go one step further in simulation tools for agriculture, this Thesis, based on the research developed, proposes a system to study and assess the effect of mobile robots in the execution of Precision Agriculture techniques. Thus, an objective is to provide a simulation environment capable of handling agricultural and robotics knowledge, through advanced tools and examples in order to introduce information in an easy and friendly way, and to allow this system to grow (objective 6, Section 1.3). This is an enormous task to be accomplished by just one research team. For this reason, and as a result of sharing extensive information in a short time thanks to current communication networks, we eventually adopted the idea of proposing an open source environment to allow different experts (e.g. farmers, designers, researchers, developers, roboticists and agronomic engineers) to offer their specific knowledge in the appropriate manner and to share it easily with experts in other areas. The proposal made in this chapter is a fundamental part of the work of Emmi et al. (2013).

3.2. System Description

The simulation tool, named "Simulation Environment for Precision Agriculture Tasks using Robot Fleets" (SEARFS) has been developed based on a mobile robot development environment that enables the analysis of performance, cooperation, and interaction of a set of autonomous robots while simulating the execution of specific actions on a three-dimensional (3D) world. The environment is capable of simulating new technological advances such as a GPS, GIS, automatic control, in-field and remote sensing, and mobile computing, which will permit the evaluation of new algorithms derived from Precision Agriculture techniques.

This environment has been designed as an open source computer application and has been developed with the purpose of providing a general programming system for the following:

1. Observing and evaluating different fleet of robots configurations while simulating the execution of various agricultural tasks (e.g. a heterogeneous fleet, composed of robots equipped with chemical and mechanical systems for weed management).
2. Implementing different types of sensor and actuator systems in a fleet of robots, and evaluating the robot cooperation behavior.
3. Generating missions for the fleet of robots, in order to observe and evaluate the acquisition of field information and the actuation for managing the field variability.
4. Representing and modeling the field characteristics in a 3D virtual universe, to attain improved understanding (e.g. modeling spatial distribution of field, soil, crop, and weed variabilities).

The SEARFS environment consists of four levels of configurations (See Figure 3.1), where the lower levels depend on the configuration of the higher levels:

- **Level 1**: At this level, the user is allowed to define the characteristics of the field where the simulation is performed. The user can model the field topography, the spatial crop distribution, the crop density, weed infestations, nutrient distributions, and other important attributes for building the decision-making systems for agricultural management. For example, it is possible to import information about a real location for the purpose of generating a virtual field with the same slope

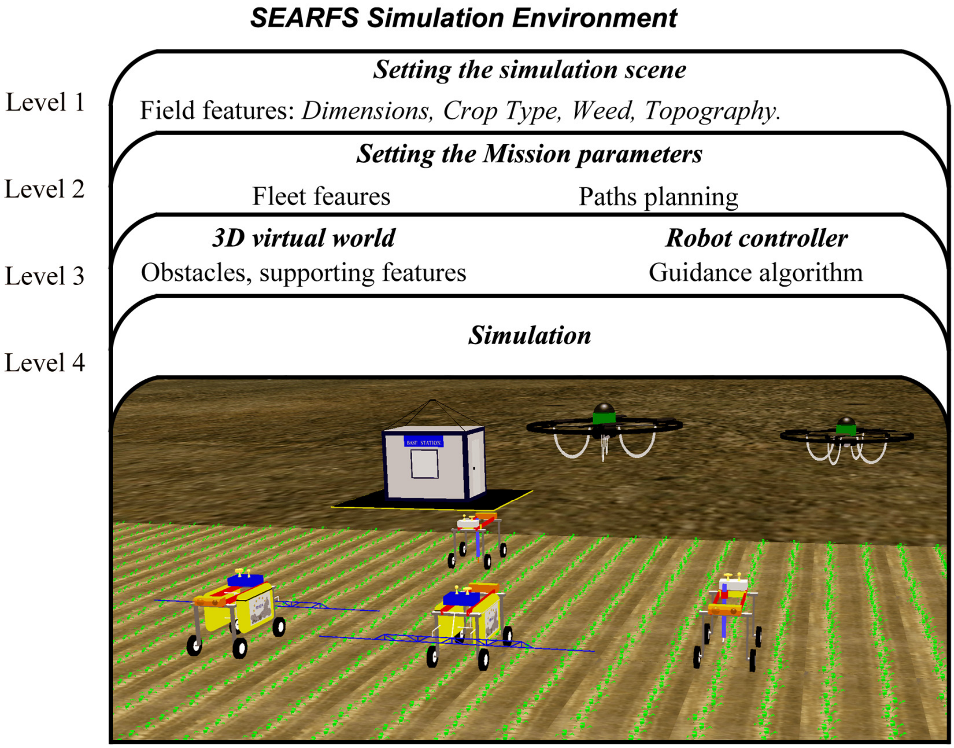


Figure 3.1. SEARFS general configuration structure, dependence of the four levels of configuration.

attributes, or to implement specific models of crop density and spatial weed distribution.

- **Level 2**: At this level, the user is allowed to establish the mission to be executed and the autonomous fleet of robots in the SEARFS environment. The mission is focused mainly on deciding the settings of the fleet, which depend on the agricultural management method and the field specifications. The user must define the type and number of robots that will perform the global mission. For each robot, a specific task will be assigned, executed through an action plan, which indicates the trajectory of each unit over the field. To ensure that each robot has the ability to execute the assigned task, the user must equip each robot with the sensors and actuators that are required for the task.

- **Level 3**: At this level, the user may perform modifications on the 3D virtual world, which are previously generated based on the information of the first two levels. The user can adjust the virtual world by adding obstacles or by modifying the field. Additionally, it is possible to add or remove robots already designed, to create or import new robot models, or to incorporate new sensory and actuation systems into the existing robots. Aside from the amendment of the 3D universe, the user must program the motion controllers of each robot to ensure that the fleet of robots executes the desired mission.

- **Level 4**: At the final level of configuration, the user may generate simulations in which the execution of the planned mission can be represented and evaluated. The simulations will offer both researchers and farmers a realistic representation and an approach to evaluate the execution of agricultural tasks in a 3D virtual crop field. The results of these simulations are expected to represent an advantage of understanding the behavior of the mobile autonomous units while performing precision agriculture techniques.

The detailed structure of SEARFS, which includes how the user can configure the different elements that make up the simulation environment and how the user can implement different algorithms and ideas that the user wants to represent and evaluate, is described in the following sections.

3.3. System Structure

SEARFS consists of two main modules: a Graphical User Interface (GUI) and a Configuration User Interface (CUI). The GUI is in charge of making a 3D representation of the working environment, including vehicles, sensors, actuators, manipulators, crops, weeds, uneven terrain, etc. In addition, the GUI allows the user to model, program, and simulate very complex mobile robots and manipulators that can be equipped with a variety of sensors and actuators, all interacting in a 3D virtual world with its elements (See Figure 3.2). The CUI is in charge of defining structures and carrying out computations to allow the user to configure the working environment in an easy and simple way (See Figure 3.2), as well as to enable the current information of the models representing the elements in the working environment to be expanded.

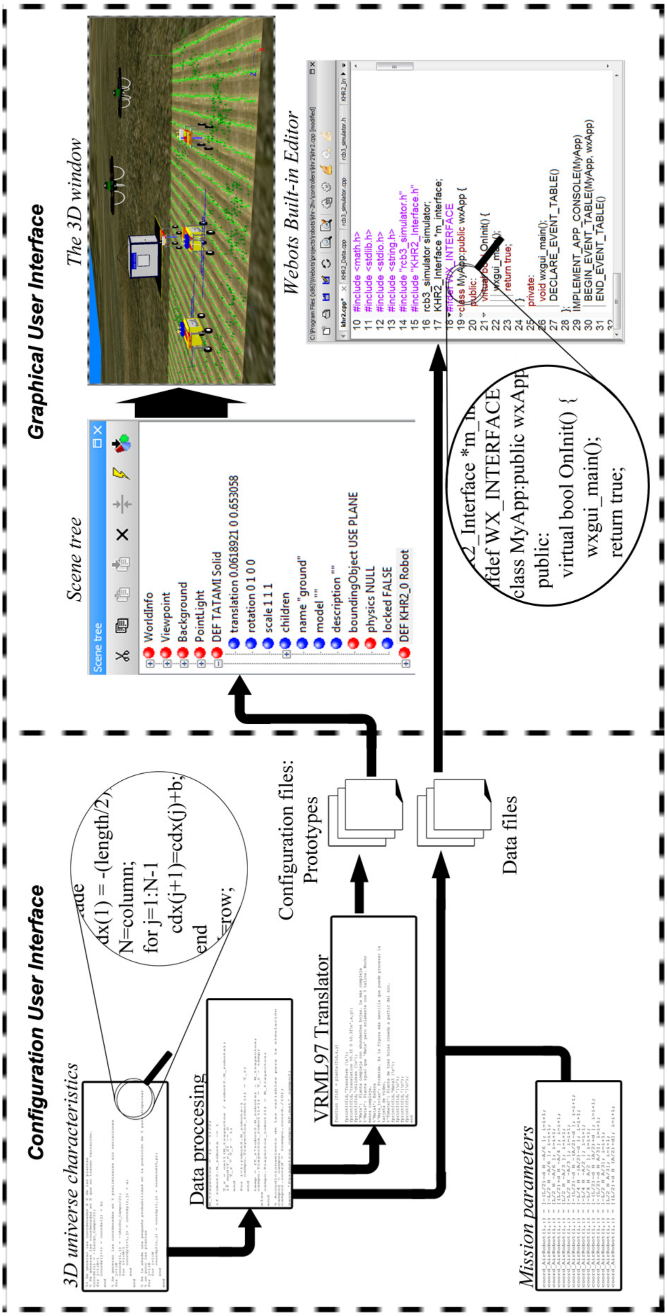


Figure 3.2. Structure of the interfaces that constitute SEARFS.

One of the main elements of the working environment is the virtual field (See Figure 3.2), in which the important characteristics defined by the user in the CUI are represented (e.g. crop, field topography, weed infestation) for a better understanding of the spatial distribution of field features, robot cooperation, and specific missions in robotic precision agriculture.

To develop the CUI module, the MATLAB computational tool has been selected (MathWorks, 2014), which is a high-level technical computing language and an interactive environment for algorithm development, data visualization and analysis, and numerical computation. This language (MATLAB) allows programming tasks to be performed faster than traditional programming languages**.** MATLAB is used worldwide and allows the user to extend the SEARFS system by defining toolboxes (a simple and efficient way of adding knowledge to the system).

With respect to the GUI, there are many different software packages on the market that provide interesting 3D features and the characteristics needed for this simulation environment (See Table 2.4); thus, this module has not been developed specifically for our application and the Webots package (Michel, 2004) has been selected because of the real support and maintenance provided by the manufacturer (Cyberbotics, 2014).

3.3.1. Graphical User Interface and Robot Simulation Tool

The Webots package allows the user to design complex robotic setups, with one or several similar or different robots. The user can create 3D virtual worlds with physical properties such as mass, joints, and friction coefficients. A large choice of simulated sensors and actuators are available to equip each robot, such as distance sensors, drive wheels, cameras, servos, force sensors, emitters, and receivers.

A Webots simulation is composed of three elements (See Figure 3.3):

1. A Webots world file that defines one or more 3D robots and the different elements that interact with the robots (See Figure 3.3, A).
2. A scene tree that describes the hierarchical order of the elements included in the Webots world file (See Figure 3.3, B).
3. A control program for each robot in the world (See Figure 3.3, C).

The Webots world file contains a description of every object: its position, orientation, geometry, appearance (such as color or brightness), physical properties,

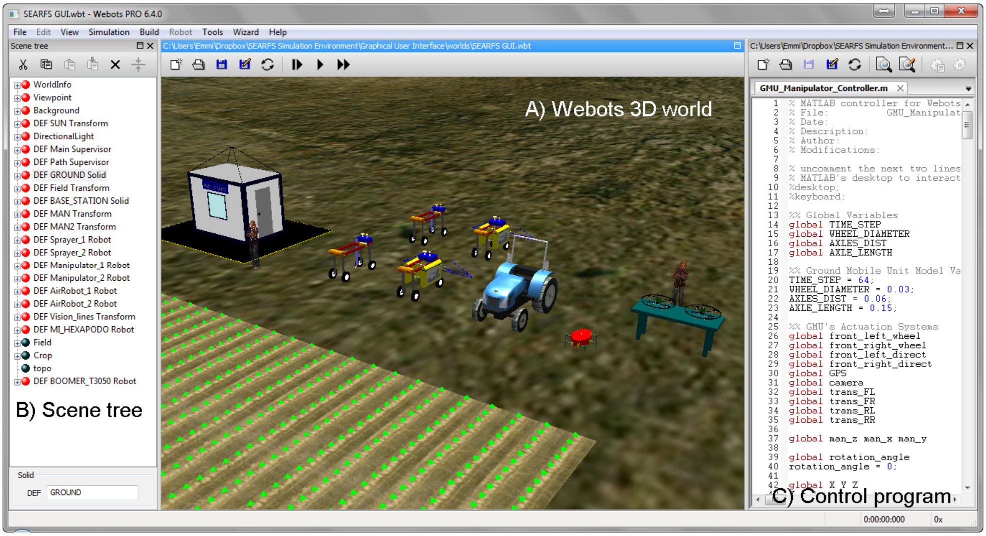


Figure 3.3. SEARFS GUI: snapshot of the general structure of the GUI.

and type of object. Worlds are organized as hierarchical structures in which objects can contain other objects.

The scene tree (See Figure 3.2) contains the information that describes a simulated world, including robots and their surroundings, and the corresponding graphical representations. The scene tree is composed of a list of nodes that are structured like a "Virtual Reality Modeling Language" (VRML), which is a 3D exchange format (Carson et al., 1999). This type of language defines the semantics that are commonly used in 3D applications today, such as hierarchical transformations, light sources, point of view, geometries, animations, fog, material properties, and textures.

The robot controllers can be programmed with the built-in Integrated Development Environment (IDE) (See Figure 3.2) or with third-party development tools.

3.3.2. Configuration User Interface

The MATLAB application provides high-level language for technical computing that allows us to quickly develop and analyze algorithms (MathWorks, 2014). With MATLAB, a user can easily manage code, files, and data, as well as program

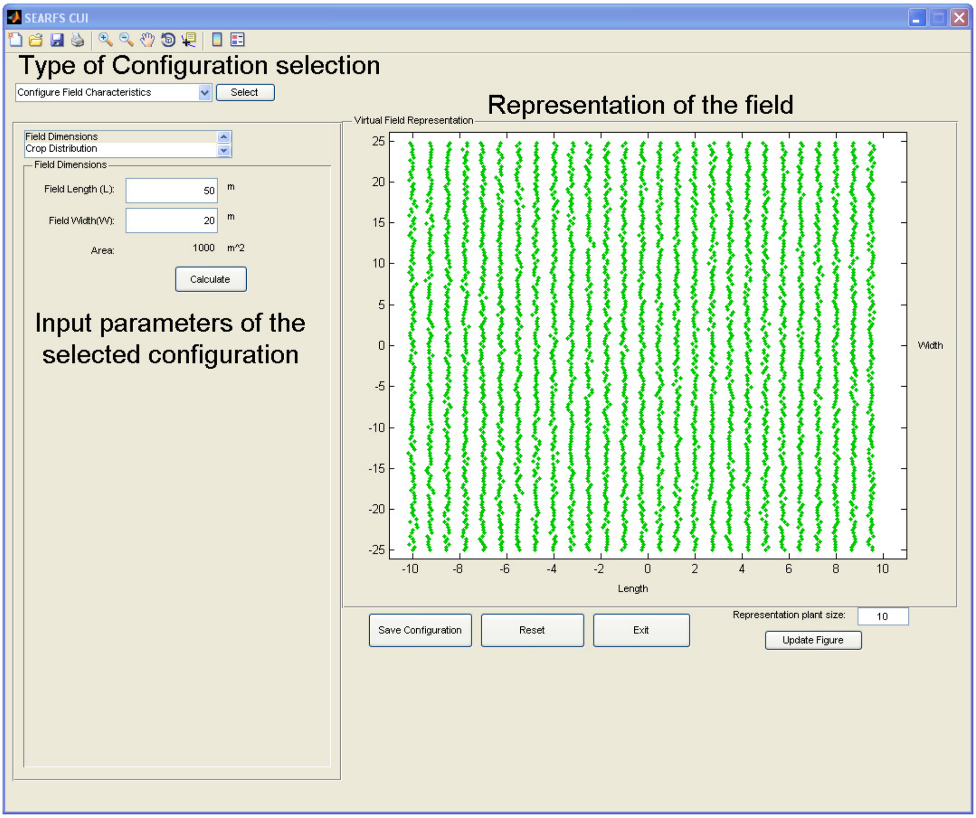


Figure 3.4. SEARFS CUI: snapshot of the general structure of the CUI.

mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, and numerical integration. Additionally, it is possible to generate 2D and 3D graphical functions for visualizing data, and to integrate algorithms with external applications and languages, such as C, C++, FORTRAN, Java, COM, and Microsoft Excel.

The CUI is used mainly for configuring the field characteristics that the user wants to represent virtually, as well as to define the parameters of the mission fleet that determine the specific task for each robot (See Figure 3.4).

To generate a realistic crop field, the environment allows the use of real information from a specific geographical location and represents that information in the 3D virtual world. The field information can be expressed by mathematical models, such as the spatial distribution of nutrients and weeds, or can be obtained by actual measurements made at a specific location that have been stored in databases.

The field information must be processed and translated to be understood by the GUI, which generates the 3D virtual world based on the VRML97 language. For this task, configuration files named “prototypes” are created that can be added to the simulation in the scene tree. This type of file generates complex 3D forms associated with the geographic information for the purpose of representing, for example, spatial crop distributions or field textures.

Some field characteristics cannot be represented by 3D shapes, such as the spatial distribution of nutrients or water. For these elements, the user can represent these field characteristics in 2D maps that could be generated by the CUI.

Other types of field information, such as field topographies, can be obtained by third-party computational tools such as “A Complete GIS and Mapping Software System – ArcGIS” (Esri, 2014) and GeoMedia (Intergraph, 2014). These tools can access databases that contain the texture of the field, which is associated with the geographic position. The CUI allows the user to create drivers to enable the interaction between SEARFS and the third-party computational tools.

Another principal function of the CUI is to allow the user to specify the assignment that each robot should execute in the simulation (See Figure 3.2). This task is performed by breaking down the general mission into different assignments for each robot. Each assignment is composed of a task that defines the type of action in the field and the path to be followed by the robot, according to the referential coordinates of the world that was created. To generate the path for each robot, the user may program different path-planning algorithms.

In order to illustrate the capabilities of the environment that has been developed, we will present a detailed configuration of some of the elements that are combined in the SEARFS environment for a specific application relating to weed control, oriented towards evaluating the behavior of the designed environment in the following sections.

3.4. Configuring the Field Characteristics

SEARFS is able to virtually and graphically represent most of the spatial variabilities that have a significant influence on decision-making systems for agricultural management (See Figure 3.5). For example, the users are able to define the real location at which they would like to perform the simulation. The characteristics that may be represented in the virtual world include field elevation, soil slope, and visual aspect. The most important feature of the field is the type of crop that is to be represented virtually. Principally, this characteristic defines the intra-row and inter-row distances of the seed line as well as other attributes that are linked to the crop type, such as the type of weed that infests the crop. To illustrate the capabilities of SEARFS, we have already included a few example algorithms to represent real field topographies and spatial distribution models for crop and weed infections. These algorithms can be the basis for other research groups and designers to enable them to include their own models.

3.4.1. Field Topography Configuration

Two models can be selected and represented in the 3D virtual field for the current development of the simulation environment:

1. A generic plain terrain.
2. A topography of a real location.

The second model is made possible by obtaining the slope and texture data from a real specific area using the Terrain Generator for Webots Tool (Cyberbotics, 2014). This tool uses the Google Maps application to select an area in the world and accesses the geographical information that is provided by (GeoNames, 2014), which generates a file that represents the topography of the area through the VRML language.

Once this file is generated, the CUI helps the user to integrate the information obtained from this database to be represented in the 3D universe correctly. The user must also define the mid-point elevation, the field crop area as well as the orientation of this area. In this sense, some configuration files are generated with the right format, in order to be interpreted by the GUI.

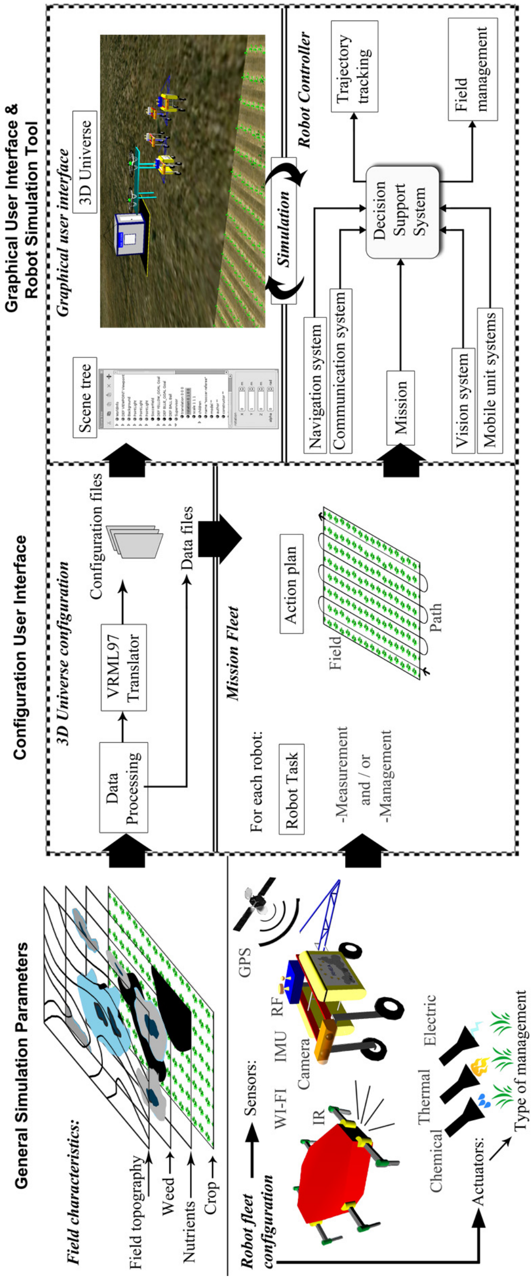


Figure 3.5. Example of the flow information between the user knowledge and the SEARFS interfaces.

3.4.2. Spatial Crop Distribution Configuration

In an agricultural application which involves mobile units, the paths of the units are often restricted, depending on the amount of damage allowed to the crop. In this regard, SEARFS allows the spatial crop distribution to be represented, since it is needed to define the paths of the autonomous mobile units. Normally, the seed lines in the field are parallel straight lines that are separated from one another by a specific distance, in accordance with the type of crop planted. SEARFS represents the seed lines in 3D shapes, thereby helping the user to better understand the agricultural task that is simulated. To accomplish this task, it is possible to configure the characteristics of the crop and to generate the plants that make up the crop.

A plant in SEARFS is represented by a cluster of complex geometric shapes that are specifically oriented, which generates a 3D form representing a single plant. The CUI allows for the selection of several types of plants to represent different crop species. The location of each plant depends on two parameters that are associated with the crop species. These parameters are the inter-plant spacing and the row spacing, which agrees with the crop spacing. To populate a field with a 3D crop, it is necessary to define the crop spacing to generate the exact position of each plant.

The current version of SEARFS contains an example model for populating a virtual field with a crop. The example model attempts to generate a sense of realism in the virtual field crop, based on observation and common knowledge. In this manner, the plants in one row are not a constant distance from the plants in adjacent rows. Instead, a small amount of dispersion regarding the position of the plants is added when the coordinate location is generated on the field, based on the idea of generating a natural positioning effect inside the field. This dispersion parameter, the two parameters for the plant spacing (inter-row distance and intra-row distance) and the dimensions of the field must be defined by the user. Following a pseudo-code of the example algorithm for populating a virtual field with a crop is presented:

<u>Example algorithm to populate a field with a crop</u>

Begin
Constant L: field Length
Constant W: field Width
Constant inter_row: average distance between plants in adjacent rows
Constant intra_row: average distance between plants in the same row
Constant σ: the variance of the inter_row distance

Previous Coordinate Y = - (L/2)
Previous Coordinate X = - (W/2)
Repeat
n = 0
Repeat
Generate a random number following a normal distribution with mean 0 and variance σ
Next Coordinate X = Previous Coordinate X + random number
Next Coordinate Y = Previous Coordinate Y + intra_row(n)*
Assign the coordinate location to a crop
n=n+1
Until – a row is finished
Previous Coordinate X = Previous Coordinate X + inter_row
Until – the field is populated entirely
End

3.4.3. Spatial Weed Distribution Configuration

A crop infestation has a high influence on the crop yield (Zhang et al., 2002). The competition for nutrients between crops and weeds is one of the main causes connected to significant reduction of crop yield. Thus, this factor should be taken into account with regard to the decision-making systems for agricultural management and must be represented in the SEARFS environment accordingly.

A weed infestation can be observed with the human eye in a real field because in most cases the weeds have different leaf shapes, textures, and color, if compared to the crop. Therefore, a weed infestation can be represented in the 3D virtual field alongside the crop. In order to do this, a mathematical representation of the weed spatial distribution is needed. The research field of this variability is very complex because it takes into account a large number of variables and works with populations of living organisms. In this sense, and given that the development of statistical models for weed representation is beyond the scope of this Thesis, we have had to find an easy way to represent a weed infestation in the SEARFS virtual field in order to meet the objectives of this Thesis.

In recent years, the impact of weeds in various crops has been studied (Clay et al., 1999; Johnson et al., 1996; Jurado-Expósito et al., 2004; Wyse-Pester et al., 2002), and some authors have attempted to represent the spatial distribution of weeds using mathematical models that relate weed growth to yield losses. But, modeling the spatial distribution of weeds is a task for the experts in this research field, and SEARFS allows validated distribution models to be included.

Therefore, in order to present an example of weed spatial distribution, we propose the following algorithm that is based on common knowledge, for the sake of simplicity. Nevertheless, other algorithms based on new findings can be provided as well.

In general, weeds are distributed neither uniformly through a field nor in a uniformly random fashion (Thornton et al., 1990). Most weeds occur in various densities as clumps or patches, in various shapes and sizes, and a few individual plants grow between the patches (Cardina et al., 1997). Based on these observations, we propose an algorithm that generates random clusters of weeds throughout the crop field, with each cluster being composed of different densities. This algorithm defines a random point inside the field crop where a weed patch is present. Based on this point, a random amount of weeds is generated, which is arranged in a random position following a normal probability distribution. As the CUI can generate a crop field based on user-defined dimensions, this model must allow the number of clusters and approximate size of the clusters to be defined by the user. Following a pseudo-code of the example algorithm for generating random clusters of weeds is presented:

Algorithm to generate a random spatial pattern for weed distribution.

Begin
Constant N: total number of weed clusters
Constant a: minimum number of weeds for each cluster
Constant b: maximum number of weeds for each cluster
Constant L: field Length
Constant W: field Width
Constant σ: the variance of the location for each weed
Repeat (for each weed cluster)
Generate a random number between –L/2 and L/2
Generate a random number between –W/2 and W/2
Assign the base location to a cluster in the field
Generate a random number between a and b
Repeat
Generate a random number following a normal distribution, using the X location as the mean of the function and a variance of σ

Generate a random number following a normal distribution, using the Y location as the mean of the function and a variance of σ

Assign the coordinate location to a weed

Until – all weeds for that cluster have a coordinate location

Until – all clusters are generated

End

Each weed is generated in the same way as the crop in the 3D field: a cluster of complex geometric shapes is placed in a specific orientation. The model of spatial weed distributions is used in the CUI to create a configuration file that locates each one of the weeds in the field.

3.5. Fleet Mission Configuration

The mission must be structured depending on the way that the user wants to establish the type of treatment for managing the variability that is present in the field. The theoretical treatment of agricultural decision analysis can be summarized as a cycle of improving observations (measurements), interpretation and evaluation (processing and planning), and implementation (actuation) (Cook et al., 1998).

There are two possible approaches when managing the spatial variabilities (Zhang et al., 2002): the map-based approach and the sensor-based approach. In the map-based approach, measurements are performed first on the field; site-specific maps are then generated by laboratory analysis, followed by actions taken on the field based on these maps. In the sensor-based approach, the desired properties of the field are measured using real-time sensors, and the variable-rate applicators are controlled based on these measurements.

SEARFS can be used to perform simulations of possible tasks that the fleet of robots could perform to manage the variability in a specific field (See Figure 3.5). Each task may be composed for a set of models, measurement, processing or actuation. The models may be evaluated and simulated, following the map-based approach or the sensor-based approach.

Not all of the tasks will necessarily be implemented efficiently with a single type of robot. This environment is composed of a set of mobile units that may be equipped with a set of sensors and actuators, which facilitate the assessment of different required tasks.

As an example of a possible fleet mission, a RHEA application for weed control has been implemented in the SEARFS environment. This mission consists of two different treatments: a chemical treatment, which can be performed by a mobile unit with a patch sprayer; and a mechanical treatment, which can be performed by a mobile unit with a 5 DOF manipulator, responsible for positioning a special weeding tool. In order to obtain information about the weed infestation, an aerial unit completes the fleet of robots configuration for this mission. This unit is responsible for obtaining the information of the infestation in the field. Each unit is equipped with a GPS and a camera.

3.5.1. Initial Fleet of Robots Available in the Environment

The SEARFS environment is initially set with a number of aerial and terrestrial units. Each unit can be equipped with different sensors and actuators to execute a specific task that is defined by the mission.

With respect to the terrestrial units, wheeled robots and legged robots have been incorporated into the environment so that the user has different fleet option settings. The advantage of using legged robots in agricultural activities is that, according to their high agility and their inherent capability of moving by using discrete contact points with the ground, the robot is able to pass between plants, thus reducing crop damage. In addition, this type of robot is able to navigate uneven terrain without needing to maintain a fixed path in the crop field, as is the case for wheeled robots.

However, depending on the crop growth stage and type, a legged robot will not always be the best option to use. In some cases, wheeled robots will be able to move along the inter-row spacing and execute the tasks that are defined by the mission. Wheeled robots, in most cases, are the best option to perform actuation tasks. These robots can be very fast in the field and can be equipped with more complex and heavier actuation systems than legged robots.

Land units are not the only units that are available on SEARFS. In past years, there has been a tendency to use aerial mobile units to obtain field information. Thornton et al. (1990) used a low-altitude helium balloon and remote 35 mm photography for mapping the wild oat distribution in a wheat field at Boghall Farm, Midlothian, UK. Further advances in Precision Agriculture (RHEA, 2014) aim to incorporate new developments in machine vision to a small quadrotor (AirRobot, 2014), with the goal of detecting patches of weeds in crop fields. In this respect, the

SEARFS environment has been equipped with an aerial unit that has been designed based on this quadrotor.

3.5.2. Sensory System

The available sensors in the SEARFS environment are as follows: accelerometer, vision camera, IMUs, range finder sensor, emitter and receiver (radio frequency, serial communication or infrared), GPS, gyroscope, light sensors, and force sensor. These sensors interact with the elements and the physical properties of the 3D virtual world, and are part of the robot simulation tool. These sensors are commonly used in a Precision Agriculture task because they aid in the movement of the mobile units across the field, avoid obstacles and establish communication between the fleet and the base station (Adamchuk et al., 2004; Lee et al., 2010; Zhang et al., 2002).

3.5.3. Actuation System

Once the characteristics of the field are known and the possible procedures have been assessed, the user must select the specific type of management for the mission. Lately, there have been several developments that involve controlled and non-uniform application of herbicides and fertilizers over the whole field whit a reduction in the applied products that decreases costs and protects the environment. For instance, Jeon and Tian (2009) implemented a direct herbicide application mechanism to an end-effector, installed in a four-wheel skid steering robotic platform. The end effector was designed specially with the capabilities of simultaneously cutting weed stems and wiping the cutting surface of the weed to apply the chemical into the weed's vascular tissues (it has a manipulator arm). Lee et al. (1999) developed and tested a real-time intelligent robotic weed control system for selective spraying of in-row weeds. The system is made up of a mobile platform, two machine-vision systems—one for guidance over the row and the other for weed detection—and a precision spraying system. In this regard, SEARFS allows a wheeled mobile unit to be configured with a patch sprayer that consists of various automatic nozzles, with a length of 4.5 m, and it is possible to control and simulate the action of each single nozzle to perform selective weed management.

In addition to the controlled application of chemicals, there has recently been a tendency to incorporate mechanical, electrical, and thermal actuation systems in autonomous vehicles or tractors. Bakker (2009) designed and implemented an autonomous system that focused on automatic weeding. This system is composed of a four-wheel steered robotic platform, which integrates a vision-based row detection system for sugar beets (he also designed a path follower). One more example is given by Chocron et al. (2007) who developed a non-holonomic robot for agriculture applications, which is a tricycle with two free rear wheels and a powered and steered front wheel. These researchers chose a hoe as a weeding tool to till the soil between the corn plant rows. In this regard, it is possible to configure the wheeled mobile unit with a 5 degree-of-freedom (5 DOF) manipulator to simulate mechanical weed management. The end effector of the manipulator can be any of the tools described above. Additionally, through the robot simulation tool, the user can simulate the actuation of these specialized tools.

In addition to the applications mentioned above, the use of robotics manipulators has been extended to fruit harvesting and gathering tasks, especially high-value crops (oranges, apples, peppers, etc.), as presented in Chapter 2. This is the case of the work developed by Van Henten et al. (2009), who design and developed an autonomous robot for harvesting cucumbers in greenhouses, consisting of an autonomous vehicle, a seven degrees-of-freedom manipulator, an end-effector for handling the soft fruit without loss of quality and two computer-vision systems for detection and 3D imaging of the fruit and the environment. One more example is given by Cho et al. (2002), who developed a robot system for harvesting lettuce plants, comprising of a three degrees-of-freedom manipulator, an end-effector, a lettuce-feeding conveyor, an air blower, a machine-vision device and six photoelectric sensors. Based on this tendency of substituting the handmade harvesting by using autonomous robots, the SEARFS simulation environment could be a mean for the study and selection of the type and configuration of manipulators and also end-effectors for autonomous harvesting purposes, using as base the wheeled mobile unit with a 5 DOF manipulator and allowing new robot manipulators to be incorporated.

3.6. Robot Controller

Once the user has configured the virtual universe, defined the mission and determined the fleet settings, it is possible to program the robot controller for each robot through the built-in editor of the simulation tool (See Figure 3.2). The controller is structured as shown in Figure 3.5, with a certain number of inputs (information that can be obtained both in “real time” or prior to the start of the task execution) and outputs (control of the various actuators that make up the robot).

The principal input of the controller is the mission to be performed, for which the information is generated at the beginning of the activities with the ground units. This input contains information on the field, such as the dimensions, the start and end points, a set of waypoints that must be traversed in order, information on the type of management, localization of the infestations, and duration of the treatment.

Other inputs for the controller are the information obtained from on-board sensors that interact with the virtual field. These sensors can determine the position of the robot in the field (GPS), locate obstacles (infrared sensors), establish communication with other mobile units in the field or simulate communication with a central base (radio frequency sensors), and measure the position, velocity, and force of each actuator in the robot.

In addition to the sensors listed above, for this type of application when robots execute an agricultural task, the guidance of the robot in the field and weed detection are usually conducted by machine-vision systems (Tellaeche et al., 2008; Tillett et al., 2002). In this sense, other important inputs can be the images that are obtained by a camera mounted on the front of the robot.

With the input information, the user can program the necessary algorithms to control the actuators that guide the robot in the field and execute the management. The SEARFS environment contains a set of drivers to establish fast and easy interaction between the user and the inputs and outputs of the controller. The users can modify or create their own drivers, depending on the use of each sensor and actuator.

As an example of a possible mobile unit controller, a simple algorithm that guides the wheeled robot through a wide row crop for herbicide application has been implemented in the SEARFS environment. This algorithm consists of a state machine (See Figure 3.6(a)) that defines four possible behaviors of the mobile unit, depending on its position in the field. The four defined behaviors are:

1. *Idle*: the mobile unit remains stationary.
2. *Positioning stage for going into the field*: when the mobile unit is outside the field and should be incorporated back into the field for further treatment (See Figure 3.6(b)).

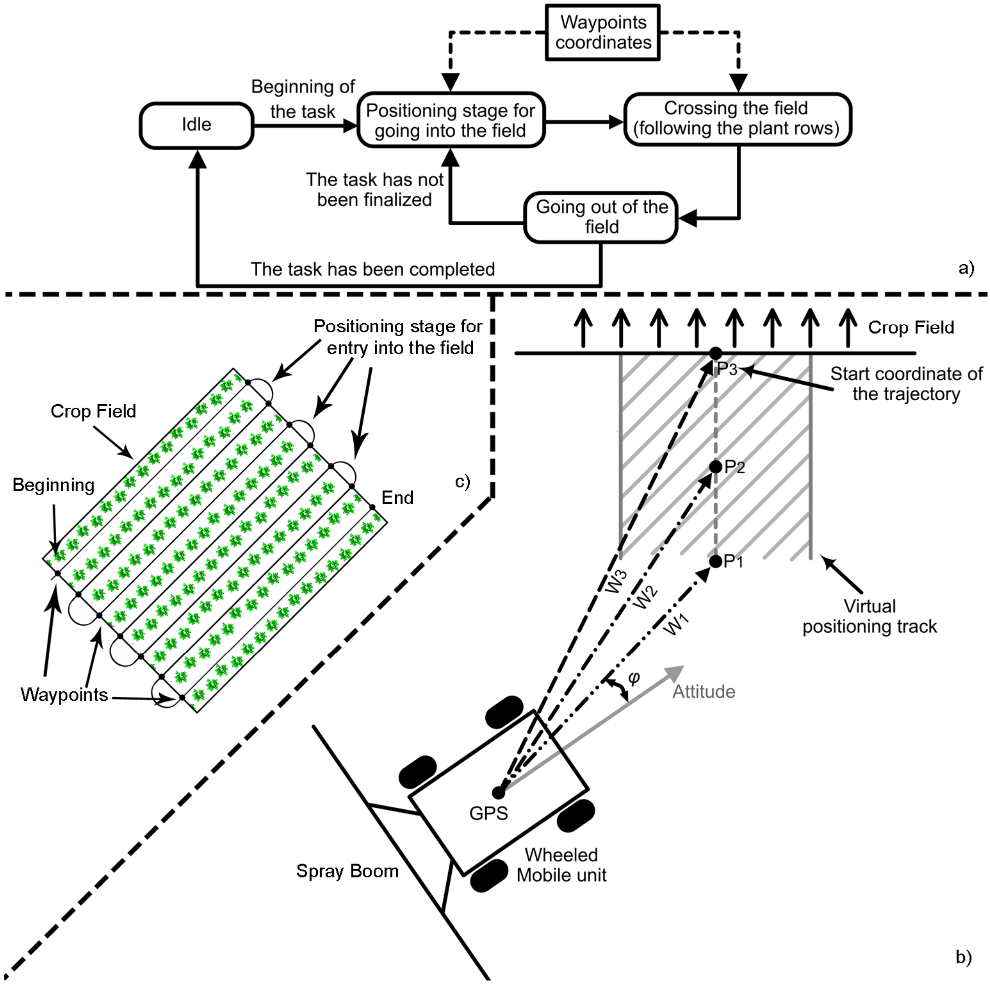


Figure 3.6. Example of a control algorithm for guiding a mobile unit in a wide-row crop field. a) Control algorithm for the positioning of the mobile unit on the crop field; b) positioning stages for going into the field; c) representation of the key points of the general mission.

3. *Crossing the field*: when the mobile unit is crossing the field, following the row crop and a predefined trajectory.
4. *Going out of the field*: the mobile unit moves away from the field at a safe distance to have an adequate margin in order to be incorporated into the field properly.

The input information for this controller is the waypoints (See Figure 3.6(c)) that the mobile unit must cross in an orderly manner (offline input), and the GPS data that indicates the coordinates of the mobile unit and its attitude (real-time input). The output information of the algorithm is the angle and the rotational speed of the front wheels.

In order to ensure that the mobile unit may be incorporated with the correct angle over the field, corresponding to the *Positioning stage for going into the field* behavior, a virtual positioning track has been designed (See Figure 3.6(b)). This virtual track ensures that, whatever the position and orientation of the mobile unit, it will enter the field correctly and will not jeopardize the present crop. The virtual track consists of three important points (P_1, P_2 and P_3), where:

1. Point P_3 represents the waypoint that indicates the beginning of the trajectory for crossing the field.
2. Distance $P_3 – P_1$ represents the virtual track length.
3. Point P_2 represents the middle of the virtual track.

At the beginning of the approach into the field, the mobile unit tries to reach point P_1. When the mobile unit is sufficiently near this point, it changes the tracking to the next point (P_2) and reduces its speed. Finally, when the mobile unit crosses the second point, it updates the tracking to the beginning of the field and waits for the state machine (See Figure 3.6(a)).

Based on these premises, the steering angle (φ) of the front wheels of the mobile unit is given by Equation (3.1), where vector $\vec{V}$ indicates the attitude of the mobile unit, vector $\overrightarrow{W_i}$ represents the position of the mobile unit with respect to the actual control point (P_1, P_2 or P_3), and *sgn* represents the sign function.

$$\varphi = \cos^{-1}\left(\frac{\overrightarrow{\mathrm{W}}_{\mathrm{i}} \cdot \vec{\mathrm{V}}}{|\vec{\mathrm{V}}| \cdot |\overrightarrow{\mathrm{W}}_{\mathrm{i}}|}\right) \cdot \mathrm{sgn}\left(\overrightarrow{\mathrm{W}}_{\mathrm{i}} \mathrm{x} \vec{\mathrm{V}}\right) \tag{3.1}$$

3.7. Interfacing with SEARFS

This section describes how the users can interact with the two interfaces that constitute the SEARFS simulation environment. Subsection 3.7.1 explains how to get started with SEARFS. Subsection 3.7.2 describes, step by step, a specific mission configuration that was used in order to generate a simulation that represents the execution of multiple tasks performed by the RHEA fleet of robots. A video was generated with the results of this simulation, which is described in Section 3.8. Finally, Subsection 3.7.3 describes the methodology for adding knowledge to the simulation environment, where the users can add their models using the benefits of the computational tool that was employed for the development of the CUI.

SEARFS has two versions: one oriented towards those who wish to evaluate different mission configurations, based on tools and models built up until now; and another version oriented towards researchers and designers who wish to incorporate new knowledge to the simulation environment. The first version does not require licensing of the software used to develop the application, but the second version does require these licenses.

3.7.1. Downloading the software packages

The users can download the latest version of SEARFS from the developer's web site (SEARFS, 2014). The web site also contains all the necessary links to execute the application (MATLAB, Webots, and others). In order to define the elements of the virtual world and to configure the fleet mission, the user must run the CUI executable file first. As indicated above, the user should follow a set of steps in order to define the characteristics of the virtual field correctly, as well as the fleet configuration and the trajectories of each mobile unit. These procedures combine the first two levels of configuration (See Figure 3.1). When the configuration is completed, the user must save the data generated by the selected models, and open the GUI application. In the GUI, all the parameters configured beforehand are represented in the virtual world automatically, and the user can organize and modify the fleet of robots, add more elements to the virtual field, and program each of the robot controllers. These procedures combine the final two levels of configuration (See Figure 3.1).

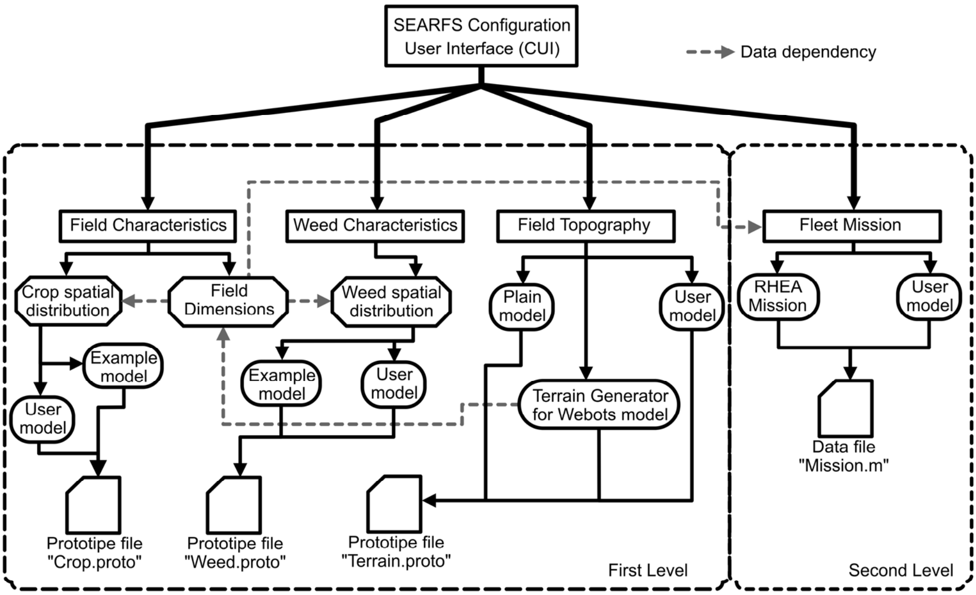


Figure 3.7. Schematic diagram of the CUI structure and data dependency.

3.7.2. Designing the Mission

The mission in SEARFS, as indicated in previous sections, contains a set of tasks assigned to each robot in the active fleet. Each task defines the type of action in the field and the path to be followed by each robot. In order to define the type of action and the associated path for a mobile unit, the working environment must be known. In this regard, the first step for configuring SEARFS is defining the field characteristics (See Figure 3.7). In order to do that, the dimensions of the field and the type of crop must be specified. Regarding the crop type definition and its virtual representation in the field, the CUI allows an example model to be selected, or calls on another model already implemented by the user (See Figure 3.7), where the name of the model and the input arguments must be introduced. When the crop coordinates are generated based on the selected model, the preliminary view of the virtual field is presented in the CUI window (See Figure 3.8). For the example presented in this chapter, a 100 m long and 50 m wide field was selected. Also, with regard to the crop spatial distribution model, the example model was selected (See Table 4), and as input arguments of this model a generic crop type was introduced:

1. 0.75 m inter-row distance.
2. 0.35 m intra-row distance.
3. 0.06 m dispersion parameter.

Both the inter-row distance and the intra-row distance parameters were selected given that coincides with the characteristics of the RHEA fields test for wide row crops, as well as the real fields test used for the assessments of the developments of this research. Once the field characteristics are configured, a weed infestation can be added to the virtual field. In order to generate the coordinates of each weed, the same procedure for the crop can be followed. The CUI allows an example model to be selected in order to generate the spatial distribution of weeds on the field, or calls on another model already implemented by the user (See Figure 3.7). When the CUI

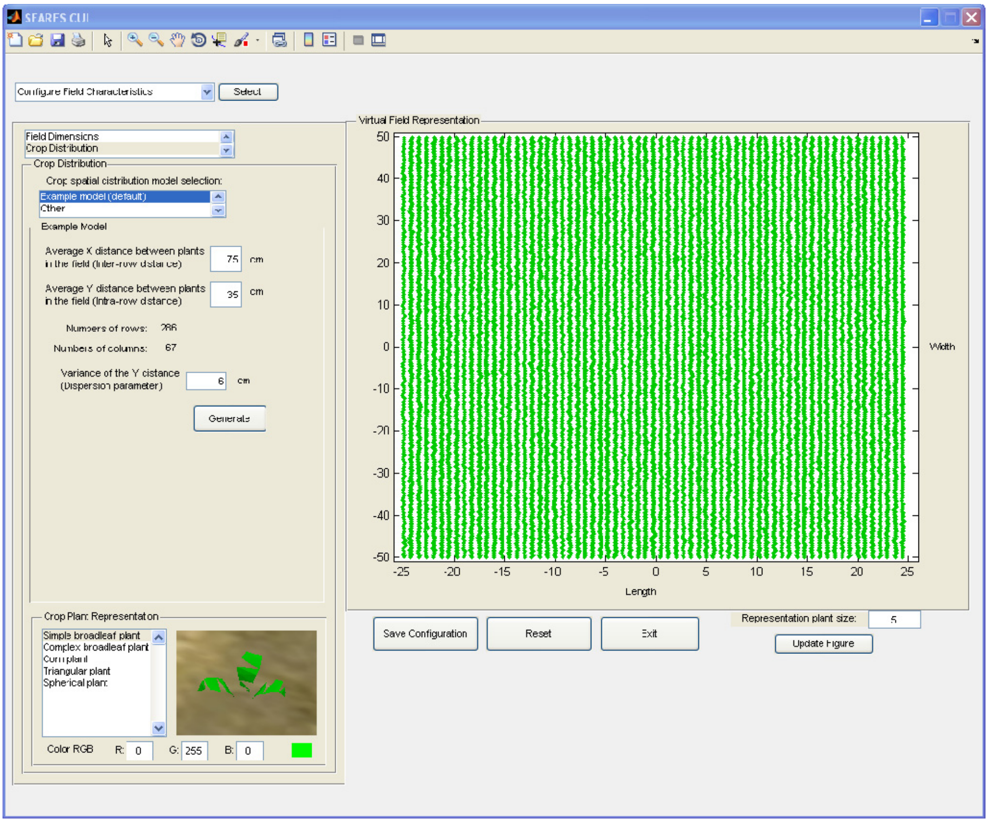


Figure 3.8. SEARF CUI: snapshot of the configuration crop distribution model window.

generates the coordinates of each weed, the preliminary view of the virtual field is updated with the weed infestation (See Figure 3.9).

For the configuration presented in this chapter, the example model for generating the spatial distribution of weed infestation was selected, with a weed infestation of 40 weed clusters, where each cluster consisted of 40 to 60 weeds, and dispersion of 0.6 m was defined for the selected model.

The next step for the configuration of SEARFS is the topography characteristics definition (See Figure 3.7). In order to do that, the CUI allows different topography models to be selected: plain field; real topography information (obtained by the Terrain Generator Tool for Webots); or a model implemented by the user. For the

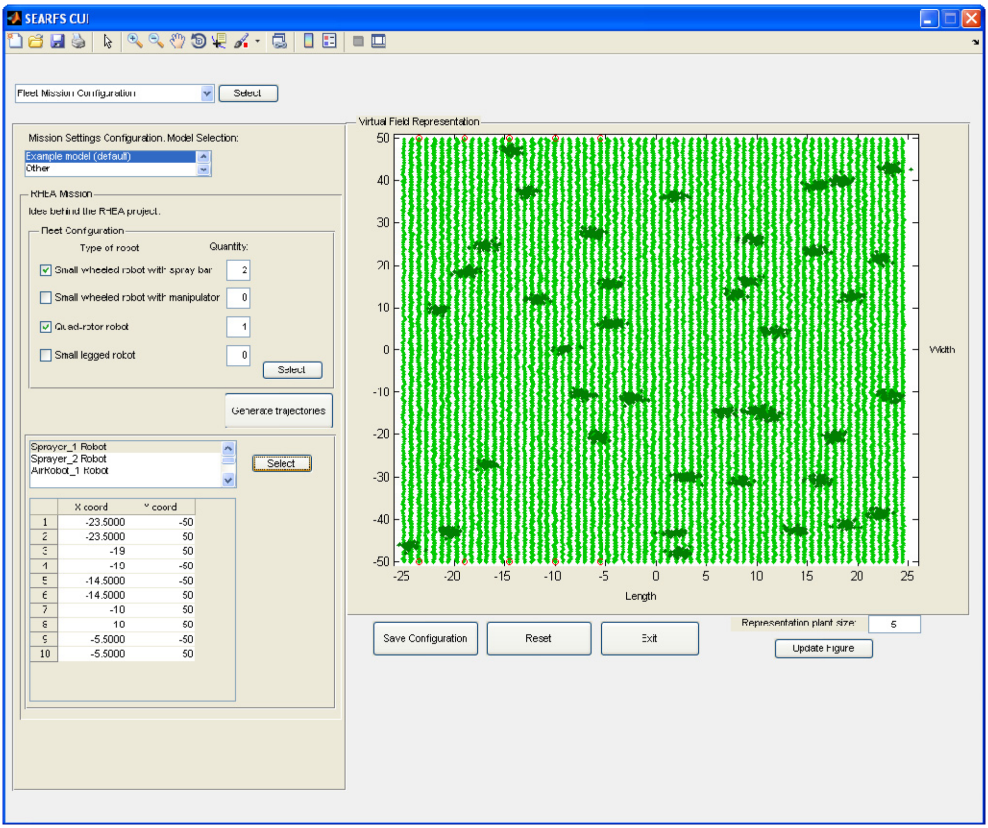


Figure 3.9. SEARFS CUI: snapshot of the fleet-of-robot parameter configuration and the mission windows view.

example presented in this chapter, a plain terrain was selected.

The final step of the SEARFS configuration is the selection of the fleet of robots structure and the path definition for each mobile unit. For the example presented in this chapter, a fleet of robots that consists of two wheeled mobile units (equipped with a patch sprayer of about 4.5 m long) and one aerial unit was selected (See Figure 3.9). At the current stage of development, SEARFS includes just one mission example: the RHEA mission for weed management (See Section 3.5). This example mission defines the coordinates of the mobile units on the field based on the structure of the robot feet selected and the field characteristics. The coordinates of each mobile unit are presented in a table in the CUI window, and the user can modify each coordinate manually in order to suit the mobile unit trajectory to a specific problem.

Once the configuration has been completed, the information is saved and the related prototype files and data files are generated. These files are read by the GUI in order to virtually represent the configured elements. At this point, the first two configuration levels are completed. To continue with the next two configuration levels, the GUI application must be opened. For the example presented in this chapter, minor changes were made in the 3D virtual world, aided by the built-in scene tree editor (See Figure 3.2), such as adjusting the position of the mobile units to an appropriate starting point. Finally, several simulations were performed with different points of view, and were then put together in a video that represents the main idea behind the RHEA project, which is presented in Section 3.8.

3.7.3. Adding Knowledge to the Simulation Environment

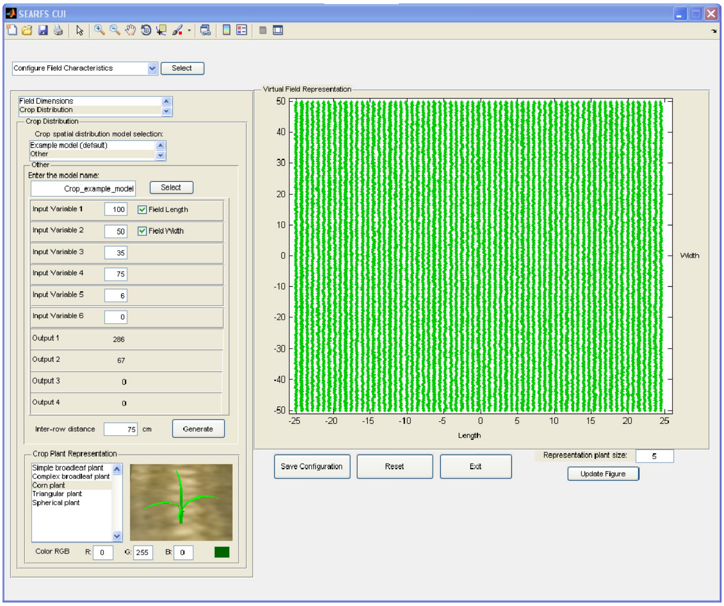
There are several ways to add knowledge to the SEARFS environment, arising from the features of MATLAB and Webots, which are summarized in the following paragraphs:

a) Implementing New Models for the Representation of the Spatial Distribution of Crops and Weeds.

The incorporation of new spatial distribution models of crops and weeds can be performed using MATLAB's philosophy of operation, that is, the use of toolboxes. The user will be able to program new models by using a template developed for this simulation environment (See Figure 3.10).

```
function [Crop_coord,out1,out2,out3,out4] = Crop_user_model (in1,in2,in3,in4,in5,in6)
% Input arguments: in1,in2,in3,in4,in5,in6.
% Output arguments: out1,out2,out3,out4.
% Type of variable for both, input and output, can be single double or single integer.

% Output variable Crop_coord is 2-dimensional 2xN matrix. The elements of
% Crop_coord are double. The first column represents the "x" coordinates, and
% the second column represents the "y" coordinates.

% The output variable Crop_coord refers to the coordinates of each plant in
% the field, where the origin of the coordinate system is the center of the
% field, at the point: O(x,y) = (0 , 0).
% Create each coordinate based on this origin point, where each coordinate
% P(x,y) must comply with the following restrictions:
% 1) -field_width/2 < x < field_width/2
% 2) -field_length/2 < y < field_length/2
% The coordinates must be in meters

% Write your Crop spatial distribution model here:




% Crop_coord(x,y) = ...;
end
```

a)



b)

Figure 3.10. Example of how to implement a new crop spatial distribution model. (a) Template file for implementing a new crop spatial distribution model; (b) SEARFS CUI window view: user crop model selection

The template defines the constraints that the input and output arguments must comply with in order to be correctly interpreted by the CUI. For example, in the case of a new crop spatial distribution model, the user has only 6 input variables of type double, 4 output variables of type double, and a 2-dimensional 2 by N matrix in which the coordinate of each plant is stored. These coordinates must be generated with respect to a specific origin frame that is given by the template. Once the model has been introduced into the template, and saved into another file, the user can call up her/his new model using the CUI, and introduce the necessary input arguments.

b) Introducing New Models of Mobile Units and Adding New Agricultural Machinery.

The incorporation of new mobile units and new agricultural machinery can be performed by using the built-in scene tree editor of the GUI (See Figure 3.2). The users have two options:

1. To create their own robot model by using the *robot node* and by adding actuation modules (*servo node*) and structure modules (*shape node*), following the composition of the VRML97 language.
2. To import robot models by using the *proto node*; models that could be designed by third-party CAD software (as VRML97 format).

c) Programming Different Controllers for the Mobile Units and the Agricultural Machinery.

In order to program new controllers for the robots (mobile units and agricultural machinery), the user can employ the facilities provided by the GUI, as is the case with the built-in source code editor, taking advantage of the application programming interface (API) functions developed for the example controllers presented in this work, or API functions already available in Webots. In addition, and according to the possibilities given by Webots for using different programming languages (C, C++, Java, Python, MATLAB and URBI), the users can import their own API functions or a full controller program.

3.8. Simulation Results

A video was generated to illustrate the concepts behind the RHEA project with an overall perspective. This video was used to evaluate the SEARFS simulation

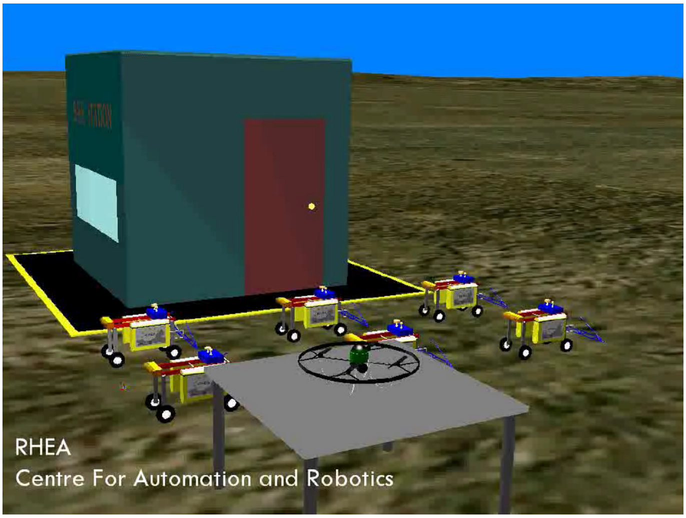
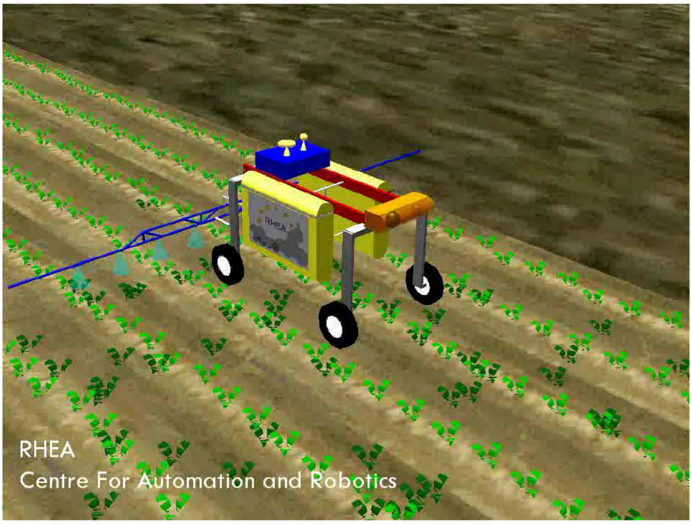


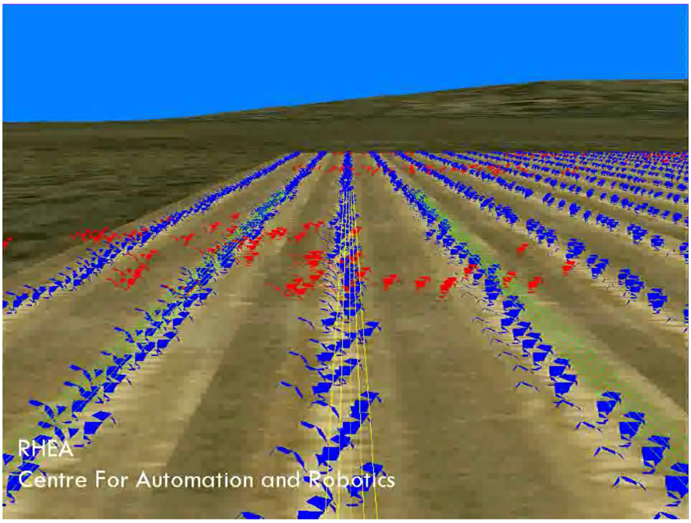
Figure 3.11. The RHEA fleet of robots in the base station.

environment and was built with different captures while running a simulation of various tasks that were performed by the units of the RHEA fleet of robots. In this case, the fleet was composed of two ground units that were equipped with an herbicide patch sprayer and an aerial unit, and the video was recorded when the system executed weed management using an herbicide (See Figure 3.11).

In this evaluation, the mission defined by the user indicates that the aerial units must first overfly the crop field, following a user-defined path, and obtain precise information of the weed infestation through a vision camera. Then, two terrestrial units use the information obtained by the vision camera on board the aerial unit to navigate the crop field and activate the individual nozzles of herbicide in the exact positions that are needed (See Figure 3.12). Each one of the terrestrial units works in a different area of the field to avoid repetition of the treatment. To follow the trajectory that is generated by this information, the terrestrial unit uses the on-board GPS and vision camera to follow the seed line and to navigate while ensuring the integrity of the crop is maintained. This video is available on the developer's web site (SEARFS, 2014).



a)



b)

Figure 3.12. (a) The terrestrial unit crossing over the crop field and activating the precise nozzles; (b) post-processed image obtained from the on-board camera of the terrestrial unit as it moves through the crop field, where the central seed line is detected, and crops (blue) and weeds (read) are differentiated.

3.9. Summary, Conclusions, and System Growth

Having noted the new scientific developments in agriculture over recent years, we can envisage a trend towards the increasing use of computer and autonomous systems to perform high-precision tasks. Furthermore, the use of computing simulators in industrial, research, and technical fields, has enabled the rapid development, visualization, and evaluation of systems and mechanisms that may be innovative. Following these trends, and based on two powerful computational tools (MATLAB and Webots), a simulation environment named SEARFS has been developed that will enable the visualization and evaluation of the execution of agricultural tasks by fleets of robots equipped with various perception and actuation mechanisms.

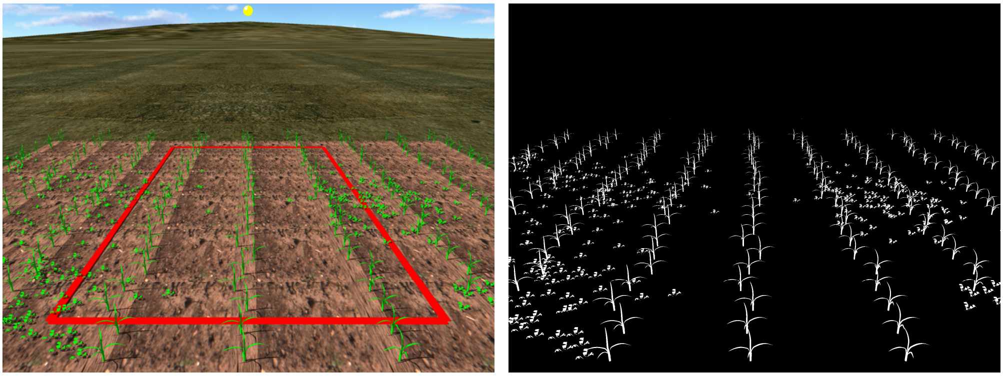
The system presented in this chapter attempts to unify two very different areas—robotics and agriculture—with the objective of studying and evaluating the implementation of Precision Agriculture techniques in a 3D virtual world as realistically as the user desires. It is therefore possible to represent real characteristics from a defined location, obtained by measurements and present in databases, and to model different variabilities that may affect the task performance accuracy of the fleet of robots. It is expected that this environment will allow a better understanding of the capabilities or weaknesses of the use of robots in agriculture, and will constitute a means for disseminating new techniques and systems that are based on Precision Agriculture. However, there is a long road ahead to proceed from the simulation study we can perform at the moment with the system described in this Thesis to practical use. Agriculture is a complex science and we will first require many different models to be included in the system (seasonality, treatment effectiveness, cost-benefit, between others) until we will be able to simulate economic justifications of different agricultural robotic systems.

The SEARFS environment is intended to be freely shared to enable people, from different disciplines and working directly with autonomous systems applied to Precision Agriculture, to use, copy, study, modify, and redistribute. This dissemination will aid in the rapid assessment of different algorithms that are applied to fleets of robots in agriculture and production simulations. This environment has the ability to create videos and snapshots, and will be useful to illustrate innovative ideas in the fields of agriculture and robotics.

The SEARFS environment is a very useful tool for validating design concepts that involve both ground and air vehicles, as well as being an exceptional device for mission analysis with fleets of robots for the RHEA project that is currently under development. The current study has a clear scope that is intended to make the simulation system available to the scientific community via the Internet. This availability will further build on the initial idea of designing an open system that will allow other researchers to extend and improve the developed SEARFS environment.

An idea about the potential of this simulation environment can be illustrated through some important research groups that have provided new models (knowledge) and uses of SEARFS, in the following terms:

1. The *Forschungszentrum Telekommunikation Wien GmbH (FTW)*, Vienna, Austria, an international center for research and development of technologies for future communication systems, which has integrated the IEEE 802.11a based communication model in the Webots platform, in order to have a more realistic approach of communication in a fleet of robots (Roca and Tomic, 2011). The new functionalities added to the simulator could help the user to understand the impact of communication on the robotic mission. This advance could be easily incorporated to SEARFS and can be used, for example, to evaluate the communication of a fleet of robots in a crop field, taking into account the dimensions, topography and the possible obstacles that the fleet could find in a real agricultural application.
2. The *Department of Software Engineering and Artificial Intelligence, Faculty of Informatics*, Complutense University of Madrid, Spain, investigated the machine vision in order to differentiate between crops and weeds in a field. The vision system was installed on board a robot and, depending on its positioning and orientation, different density values with diverse accuracies were obtained for the same distribution of plants in the field. Both intrinsic and extrinsic parameters of the camera are critical for density values and their accuracy. In this regard, through the SEARFS environment (Guerrero et al., 2012), the Department analyzed the dependency of the accuracy of green density detection with respect to the camera pitch angle, aided by the possibility of simulating a camera and generating a virtual crop field infested with weeds (See Figure 3.13).

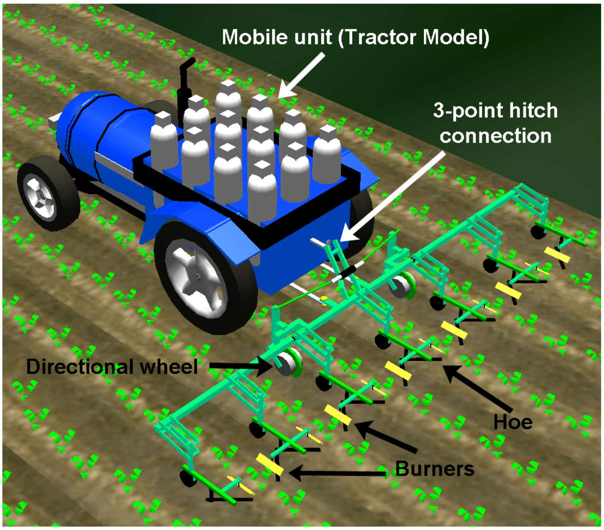


a) b)

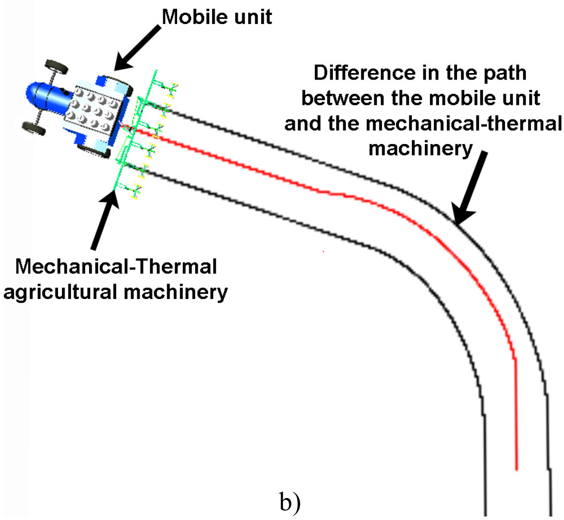
Figure 3.13. Preliminary results of the simulations performed by the Department of Software Engineering and artificial intelligence, Faculty of Informatics, Complutense University of Madrid. (a) Image captured by a simulated camera in a maize field; (b) processed image as a precursor to differentiating between crops and weeds.

3. *Cyberbotics*, the company that develops Webots, designed a tractor model (Boomer T3050) from the CNH company (See Figure 3.14). It has offered to incorporate this model into the next version of SEARFS, with the objective of making a more accurate tractor model available.

Figure 3.14. A three-dimensional model of the Boomer T3050.



a)



b)

Figure 3.15. Example of new design of mobile units in SEARFS. (a) Three-dimensional model of the mechanical-thermal agricultural machinery developed by the Dipartimento di Agronomia e Gestione dell'Agroecositema, Sezione Meccanica Agraria e Meccanizzazione Agricola, University of Pisa, and a new model of a wheeled mobile unit; (b) preliminary results of the simulation for evaluating the behavior of the machine.

4. The *Dipartimento di Agronomia e Gestione dell'Agroecositema, Sezione Meccanica Agraria e Meccanizzazione Agricola*, Pisa University, Italy, is investigating new Precision Agriculture techniques in order to perform weed control using thermo-mechanical procedures. In this regard, it has developed agricultural machinery that consists of a set of burners for thermal weed control within the intra-row spacing, and a set of hoes for mechanical weed control within the inter-row spacing (Peruzzi et al., 2011). Based on this design, a 3D model of the operative machine has been developed in SEARFS (See Figure 3.15), in a bid to assess its performance, time constraints and dynamic behavior, while executing weed control autonomously. In addition, a new model of a wheeled mobile unit (See Figure 3.15) has been developed for the purposes of handling this category of machinery.

As part of the expansion of SEARFS, it would be interesting to allow the user to configure more characteristics of the agricultural field, such as historical and present yield distributions, physical soil properties, and different types of infestation. Furthermore, it would be interesting to program different drivers to obtain topographical information about the field through other databases that are mentioned above.

In this chapter, we have presented a simple model that attempts to represent a spatial representation of weeds in a crop field. It would also be interesting to add new models of spatial distribution of weeds in SEARFS. With this work, we therefore intend to encourage the scientific community and experts to incorporate validated models to the simulation environment.

One of the main tasks that would help the system grow and bring it to the next level would be to provide it with greater intelligence, with the objective of developing new structures for mission designing. Only one mission has been implemented in the current stage of SEARFS, although by adding the possibility of defining new missions that could be based on Artificial Intelligence (AI) techniques and by including new validated models of field variabilities, this simulation environment could become an everyday tool in the future of Precision Agriculture.

The SEARFS simulation environment is a first step to have an operational fleet of robots for precision agriculture working in cooperation and executing diverse task simultaneously. This computational tool enables the design and implementation of the necessary models for emulate an autonomous system in operational conditions with the purpose to be used as intermediate step for the validation of new control architectures for multi-robot system in agricultural field. The following step to be performed in order to obtain a system capable to accomplish this assessment could be the implementation of new models for communicating real autonomous vehicles controllers to the SEARFS simulation environment, where the sensory system and the actuators response comes from the models implemented in SEARFS, and the decision making derives from specialized algorithm in the real controller. The SEARFS environment is the perfect tool for configuring and validating (fully or partially) the design concepts proposed in the following chapters.

The SEARFS simulation environment is available for downloading on the developer's web site (SEARFS, 2014).

Chapter 4

Control Architecture for Autonomous Agricultural Robots

4.1. Introduction

To obtain a fully autonomous agricultural system, the two general frameworks presented in Chapter 2 must be merged in an architecture (hardware and software) sharing the sensorial system and the planning methods for both the autonomous guidance and the autonomous treatment. This task must be performed with the objective of reducing the amount of hardware while maintaining the required system performance. This architecture must be capable of integrating different sensor and actuation devices developed by diverse research groups as well as different types of commercial equipment. Furthermore, it must be flexible and integrate several standard communication protocols that are common in high-tech agricultural applications (Hinterhofer and Tomic, 2011). A modular architecture to provide convenient settings of the interfaces between the sensors and devices and proper organization of the perception, processing, and actuation of these types of systems are required due to the large variety of available technologies.

Thus, this Thesis focuses on identifying proper structures for mobile autonomous vehicles collaborating as a fleet of robots in agricultural tasks. Hardware reliability, truly plug-and-play features, and programmability are essential for efficient agricultural vehicles and, consequently, for competent fleets of robots, but modularity, expandability, ergonomics, maintenance, and cost are also of paramount importance to increase the number of prospective real applications in agriculture.

The aforementioned basic features are to be considered in the proposed configuration; however, other features are also discussed in the following sections with the primary aim of providing manufacturers of agricultural machinery with solutions for automating new developments, particularly in precision agriculture, an emerging area demanding robust and efficient solutions.

As mentioned in the previous chapters, the work presented in this Thesis has been conducted within the RHEA project, which focused on the development of a new generation of vehicles for effective chemical and mechanical management of a large variety of crops to minimize the use of agricultural inputs to decrease environmental pollution while improving crop quality and safety and reducing production costs. To accomplish this aim, RHEA conducted research in (a) advanced perception systems to detect and identify crop status, including crop row detection, and (b) innovative actuation systems to apply fertilizers and herbicides precisely as well as to remove or eliminate weeds directly. Additional research is focused on the development of (c) a fleet of small, safe, reconfigurable, heterogeneous, and complementary mobile units to guarantee the application of the procedures to the entire operation field. This scientific activity must be complemented with technical developments in (d) novel communication and location systems for robot fleets, (e) enhanced simulation systems and collaborative graphic user interfaces, and (f) pioneering fuel cells to build clean and efficient energy sources (See Figure 4.1).

To accomplish these overall goals (objectives 3, 4, 5, and 7, Section 1.3), we have developed the structure presented in this chapter, which is organized as follows. First, the architecture of an autonomous system is introduced in Section 4.2; in Section 4.3, we collect the requirements for agricultural fleets of robots; different topologies for fleets of robots are discussed in Section 4.4; finally, Section 4.5 presents some results, followed by conclusions in Section 4.6. The proposal made in this chapter is a fundamental part of the work of (Emmi et al., 2014a; Emmi and Gonzalez-de-Santos, 2012)

Figure 4.1. The RHEA fleet (ground mobile units and implements).

4.2. Structuring a Fully-Autonomous, Agricultural System

Analyzing the presented problem, the first idea that comes to mind in order to structure a fully- autonomous, agricultural application is to take two operational subsystems: one autonomous vehicle and one autonomous implement, and put them together working independently. This, of course, entails a huge amount of problems in order to make the system work properly in a given environment executing a given target task. Leaving the mechanical connection aside and assuming that both subsystems are compatible, thanks to the current standards in agriculture, the first thing that must be ensured is that the moving behavior of the entire system (absolute position and orientation of each subsystem) must be single, and in accordance with the type of crop and the target task. In other words, the autonomous vehicle that guides the system must guarantee that, at any instant, the application point or area of the autonomous implement is in the desired location, which is what a driver would do in a standard agricultural application. Not only these localization and control problems are presented, but also the stability, safety, robustness and efficiency of the system are other aspects to be taken into account when structuring the entire autonomous system.

Therefore, a communication mechanism must be present between the autonomous vehicle and the autonomous implement, in the form of a main controller responsible to merge the desired behavior of each individual subsystem in one single behavior, and treats the fully autonomous agricultural system like a robot unit. Thus, the whole system can be broken down into three main modules: vehicle, implement, and controller.

4.2.1. The Vehicle

The vehicle is the module in charge of ensuring the motion behavior of the implement (absolute position and orientation) and must adapt both the type of crop and the type of operation on the crop. Normally, the vehicle carries or tows the implement and therefore provides the necessary energy to the implement as well. Thus, the vehicle must include mechanical adaptors (three-point hitch) to fulfill agricultural standards, electrical generators, and hydraulic pumps. These specific subsystems are provided by commercial agricultural vehicles, and thus adapting a commercial agricultural tractor to configure an autonomous vehicle is easier and more efficient than developing an agricultural robot from scratch. This also allows the developers to advance system integration and testing while avoiding other time-consuming activities such as chassis design, manual assembly, testing, and vehicle homologation, for instance. These modifications drastically increase vehicle reliability by using long-term tested items (engine, braking, steering and transmission systems, housing, etc.) while decreasing time until availability. The safety, robustness, and efficiency of the system must also be considered when structuring the entire autonomous system.

The final selected vehicle for the RHEA project was a CNH Boomer-3050 (51 hp – 37.3 KW, 1200 kg), whose restructured and empty cabin was used to contain the computing equipment for the perception, communication, location, safety, and actuation systems. In addition, some systems require the placement of specific elements outside the cabin: vision camera, laser, antennas (GPS and communications), and emergency bottoms. This overall equipment can be classified into the following subsystems:

1. A weed detection system to detect weed patches that relies on machine vision
2. A crop row detection system to help steer the vehicle based on machine vision
3. A laser range finder to detect obstacles in front of the mobile units
4. Communication equipment linking the operator station, the mobile units, and the user portable devices
5. A two-antenna GPS to locate/orientate the vehicle in the mission field
6. An IMU to complement the GPS data and enable improved vehicle positioning
7. A vehicle controller in charge of computing the steering control law, throttle, and braking for path tracking purposes. Steering, throttle, clutching, and braking are the mechanisms normally provided by modern vehicles via a controller area network (CAN) bus
8. A central controller as a decision-making system responsible for gathering information from all perception systems and computing the actions to be performed by the actuation components
9. An additional energy power supply based on a fuel cell, which is monitored by the central controller

Figure 4.3(a) and Figure 4.3(b) illustrate the original and modified Boomer T3050, respectively. The latter image shows the reduced cabin, the fuel cell, and the solar panel placed on top of the robot, the antenna bar and the equipment distribution inside the cabin. These two last elements are magnified in Figure 4.3(c) and Figure 4.3(d).

4.2.2. Implements

The implement is a device designed to perform an action on the crop, such as herbicide and pesticide booms, and mechanical and thermal weed removers. The nozzles and burners found on implements are normally operated independently to focus the actuations according to precision agricultural principles. Some of those elements have positioning devices to improve treatments. PLCs and computers are used to control those independent elements and coordinate actions with the vehicle.

We based the controller structure features on the three diverse implements developed in the RHEA project:

(a) (b) (c)

Figure 4.2. Implements controlled by the RHEA system: a) patch sprayer, b) physical weed control; c) canopy sprayer

a) A patch sprayer (Carballido et al., 2012) for herbicide application in cereals (See Figure 4.2(a)), which consists of a 5.5 m boom containing 12 nozzles separated by 0.5 m and exhibiting independent actuation. The implement is carried by the vehicle and contains two herbicide tanks (200 L and 50 L, respectively), the contents of which can be mixed to apply different treatments. The flow of herbicide through the nozzles as well as the implement folding/unfolding device is controlled by the vehicle's main controller.

b) A machine for physical weed control (Peruzzi et al., 2012) in flame-resistant crops such as maize, onion, garlic, etc. (See Figure 4.2(b)). This system consists of four couples of burners attached to a main frame that tackles four consecutive crop rows. The implement is towed by the vehicle, which is also responsible for controlling the relative lateral position of the implement with respect to the vehicle's position. The flame intensity of each burner is a function of the amount of weeds detected by the weed detection system based on machine vision. That amount is expressed as the percentage of the area covered by weeds in every area unit – typically 0.25 m × 0.25 m. The vehicle's controller is also in charge of the folding/unfolding device.

c) An airblast sprayer (Vieri et al., 2012) for pesticide application in olive trees (See Figure 4.2(c)), which consists of two vertical booms with four nozzles each. The lower and upper nozzles are oriented by stepper motors based on the information provided by a set of ultrasound sensors, one per nozzle, with the aim of maximizing the amount of pesticide applied to the canopies. The vehicle passively tows the implement, which contains all of the sensorial systems required for the aforementioned application.

The aim of this subsection is simply to illustrate the large number of different types of sensors and actuators used in these implements. Thus, the detailed aspects of these designs are considered outside of the scope of this Thesis.

4.2.3. Main Controller

The main controller is in charge of steering the vehicle accurately, coordinating the actions of the vehicle, and maintaining communication with the operator. In addition, the main controller integrates a large number of subsystems, such as those

Figure 4.3. (a) Initial commercial tractor; (b) final RHEA mobile unit; (c) external equipment onboard the mobile units and (d) internal equipment distribution inside the mobile unit's cabin.

mentioned in Chapter 2. Integrating different systems based on diverse communication technologies, operating systems, and programming languages leads to questions about the organization of the hardware and software architecture, which can be centralized or distributed, open-source or commercial development software, among others, options that have pros and cons.

4.2.3.1. Centralized vs. Distributed Architecture

A centralized architecture relies in a single computer to run all applications in the system. This structure provides the following advantages:

1. Maintenance is easier regarding updates and security.
2. Use of a single operating system and typically a single programming language.
3. A single location to handle events and alerts.
4. A single place to access and handle applications and information.
5. Single memory space to rapidly share data.

Nevertheless, this architecture presents several drawbacks:

1. As network elements are added, it may be difficult or expensive to scale the system to handle the load.
2. All peripherals are queried from a single location.
3. This architecture is not redundant or fault tolerant.

However, a distributed architecture is based on several computers running different applications on similar or dissimilar operating systems. They are connected by a communication network or point-to-point communication links. This structure has several advantages:

1. Adding new peripherals is an easy task.
2. A computer only handles the peripherals relevant to its application.
3. This structure provides greater computing power.
4. It can be fault tolerant if the software is designed for fault tolerance.

Nevertheless, this architecture has several disadvantages:

1. Maintenance is costly in terms of updates and security.

2. Different operating systems and programming languages can be used, and thus, there are many applications to consider.
3. Management of the network may be difficult and time consuming.
4. The network introduces delays in communicating data, which may impair the system real-time features.

By considering the advantages and shortcomings of both configurations, the optimum choice will depend on the specific application, that is, the number of sensors; the number and type of peripherals; the number of different computers, including operating systems and languages used; the required computing power; and the real-time requirement, among other factors. This task is relatively easy to perform in a closed requirement system, i.e., a system in which we know the exact number of subsystems and their features. However, in agriculture, the number of different system configurations, the available commercial devices and custom-made equipment make the selection of the optimum configuration a difficult task, in particular due to the different operating systems and languages.

The best solution, as in other engineering fields, could be to use a hybrid architecture featuring centralized and distributed characteristics capable of integrating new systems when possible and permitting the connectivity of the complex system by using distribution features, such as Ethernet networks and a CAN bus, among others.

4.2.3.2. Open-Source Software vs. Commercial Development Software

In the last ten years, developers of robotic systems, particularly universities and research centers, have been attempting to consolidate and package robotic frameworks as open-source software available to the entire robotic community. Examples of these frameworks are CARMEN (2014), MOOS (2014), PLAYER (2014) and ROS (2014), among others, which are essentially network-based communication architectures that allow diverse nodes or applications to communicate and interact with each other. These applications are packages developed by other research groups or by the users, and they are commonly used in the academic community and research centers and commonly applied in service robots. This trend, packaging a robotic framework, facilitates the integration of systems from different providers with very dissimilar features by using open-source models. The advantages of open-source software over closed-source (proprietary) software are normally summarized as follows:

1. Individuals and small companies support the development of the software and thus reduce the number of programmers. Thus, the development cost is decreased.
2. Bugs are found and fixed faster because there are more people analyzing the code.
3. Shorter development time due to the reuse of code.
4. An open source project allows one to be more independent. No problems arise due to developers leaving the company.

Nevertheless, open-source software also leads to the following problems:

1. Revealing the know-how. Making the software code available to others may cause replication and loss of financial benefit.
2. Loss of income through sales. Revenue must be gained through support agreements and OEM customization.

Currently, the most popular open-source operating system for robots is ROS (Robot Operating System), a software platform comprising a large collection of open-source libraries and tools that was initiated in 2007 for the development of robot software and provides the functionality of an operating system on a heterogeneous computer cluster. This system provides standard operating system services (hardware abstraction, device control low-level message passing between processes, implementation of commonly used functions, and package management). ROS is the reference in many research and academic developments because it is free and powerful, but it is released under the terms of the Berkeley Software Distribution licenses, a family of permissive free software licenses that imposes minimal restrictions on the redistribution of covered software, complicating its application to systems for commercial exploitation (Stallman, 2014).

Apart from thus discussions about pros and cons of using open-source software, some researchers have recently suggested that ROS should be locked down, protected, and commercialized (Cousins, 2012) to monetize industrial and service robots (Tobe, 2014).

4.3. Identifying Architecture Requirements for Agricultural Fleets

4.3.1. Fully Autonomous Agricultural System Requirements

As presented in Sections 4.1 and 4.2, the problem is summarized as structuring a hardware architecture for a fully autonomous agricultural system (vehicle and implement) as a part of a fleet of robots capable of executing diverse agricultural tasks. An important aspect of structuring this architecture is the reduction of the amount of sensors and actuators of the entire system, which constitute the basis for the design. However, decreasing the amount of devices for sensing and acting is a difficult task because these components are needed for the correct operation of the system.

Analyzing the two general frameworks presented in Chapter 2 (See Figure 2.2 and Figure 2.3) reveals that some tasks for guidance and actuation require similar sensorial systems and similar information processing, particularly the tasks of localization, perception, and planning. Furthermore, in a fully autonomous system, instead of having two processes for each of the aforementioned tasks, which would replicate hardware and software elements, these similar tasks can be merged to reduce the amount of specialized hardware.

When merging the tasks of each individual subsystem, the problem of resource assignment and synchronization arises. In addition, the vehicle and implement move according to different reference frames, but a general behavior of the fully autonomous agricultural system must be determined as a part of the general mission of the entire fleet of robots.

Another key element of the hardware architecture is the ability to allow diverse vehicle and implement configurations to enable a fleet of heterogeneous robots to execute diverse crop operations at the same time. To achieve this capability, the hardware architecture must be modular to allow diverse sensorial and actuation elements to be rapidly and easily replaced, installed, and configured, thus modifying a small part of the fully autonomous system to enable diverse crop operations. The link between sensors and actuators relies on the computer system.

Given this preliminary discussion, agricultural fleets of robots should rely on the following elements:

1. A hybrid computing system consisting of a central, powerful, truly real-time, multitasking computer with fast network communication features to connect different peripherals.
2. The central computer should have a large family of real plug-and-play hardware modules including both reliable wired and wireless communication modules.
3. The central computer should provide capabilities to facilitate running software developed for different platforms and in different languages
4. Simple and powerful connections to external libraries and third-party tools must be included.
5. The development tools must allow diverse programming languages for different applications and domain experts in different disciplines (e.g., agronomists and roboticists) and must permit multidisciplinary use, e.g., a graphic programming system.
6. The central computer should allow a wide variety of data acquisition and embedded control devices, which tightens software-hardware integration.
7. The central computer should be ruggedized to operate in harsh conditions and allow intrinsic parallelism: multicore-ready design and support for different hardware acceleration technologies: DSPs (Digital Signal Processing), FPGAs (Field-Programmable Gate Array) and GPUs (Graphic Processing Units) as coprocessors.
8. The central computer must have the capability to execute and solve complex algorithms in real-time using real-world external signals (A/D).
9. The entire architecture must be able to transition easily from academics to industry, ensuring protection of property rights.

Many of these features are fulfilled by the new family CompactRIO-9082 (cRIO-9082: 1.33 GHz dual-core Intel Core i7 processor, 32 GB nonvolatile storage, 2 GB DDR3 800 MHz RAM), high-performance integrated systems commercialized by National Instruments Corporation, whose equipment has already been used in some unmanned road vehicles (Courrier et al., 2014; Ramirez et al., 2007) and autonomous agricultural vehicles (Bakker et al., 2010b). The selected system offers a powerful stand-alone and networked execution for deterministic, real-time applications. This hardware platform contains a reconfigurable field-programmable gate array (FPGA) for custom timing, triggering, and processing and a wide array modular I/O for any application requirement. This system is designed for extreme ruggedness, reliability, and I/O flexibility, which is appropriate for the integration of different sensorial and actuation systems in precision agriculture autonomous applications.

Furthermore, LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a graphical programming environment used to measure, test, and control different systems by using intuitive graphical icons and wires resembling a flowchart. This environment facilitates integration with thousands of hardware devices, provides hundreds of built-in libraries for advanced analysis and data visualization, and can help prototype applications with FPGA technology.

These hardware/software features ensure (a) performance: equipment reliability and robustness in harsh environments; (b) compatibility: a large list of modules are available for peripherals, including serial and parallel standard communications; (c) modularity/expandability: a computer-based system includes a set of configurable modules that allow the system to grow according to the application needs; (d) developer community: the increasing number of LabVIEW users share their experiences and developments in the form of packages or functions freely and openly through blogs and forums; and (e) cost: while the investment in NI hardware and software is initially high, profitability must consider the reduction of the development in person-months as well as the reduction of the hardware when manufacturing medium-to-large prototype series by using products such as the Single-Board RIO, in addition to the guarantees provided to the commercial establishments for the developments of new systems and products.

Based on the previous analysis of both hardware and software features, we have proposed the aforementioned system as the Main Controller of the RHEA fleet of robots (Gonzalez-de-Santos et al., 2012). Key features in the selection of the present controller were the capabilities of configuring a minimum hardware and assuring a short period for software development. These features allow the developers to focus on the implementation of new algorithms and on the integration of sensors and actuators.

4.3.2. Fleet Management Topology Requirements

Once the architecture requirements for the implementation of a fully autonomous agricultural system is defined, it is necessary to define the requirements for the fleet of robots, which comprises several robot units as described in the previous sections, oriented to agricultural applications. Basically, a fleet is a set of independent mobile units that must be coordinated somehow and interfaced with a) the environment or workspace; b) with each other; and c) with an operator, at given instants. In robotic agriculture, the workspace normally is well known: the dimensions of the field or set of fields are well demarcated; the field is planted or needs to be planted with a specific crop; the boundaries and fixed obstacles are well known; and the areas where the vehicles can travel are well determined. In addition, coordinated motion in this workspace involves relatively small teams of both similar (e.g., tractors with patch sprayers) and/or heterogeneous vehicles, (e.g., harvester and truck), depending on the application and the final goal. Each of these situations leads to diverse solutions of the coordinated motion problem. In some applications, where two or more vehicles must constantly cooperate (e.g., autonomous harvesting), motion coordination between nearby vehicles is more critical to ensure path accuracy, dead distance, time, fuel or other efficiency criteria than in other applications in which each vehicle performs a defined and repetitive task without cooperation (e.g., transplanting and weed control). Some attempts have been made to solve the coordinated motion problem in the form of conceptual Farming System Architectures (Bochtis and Sørensen, 2009, 2010; Eaton et al., 2008; Sørensen et al., 2010; Vougioukas, 2012), including some that have put cooperation between robots in agricultural tasks into practice (Johnson et al., 2009; Moorehead et al., 2012).

However, given the workspace characteristics and the well-defined general objective of the fleet, many authors agree that a central planner running on an external computer that knows each of the elements involved in the agricultural application and is capable of readjusting the parameters and assignments is necessary for optimal development of the general agricultural task. However, depending on the type of agricultural application for which the fleet is configured, each autonomous unit could have a greater or lesser ability to re-plan its own sub-tasks. Conceptual examples can be found in (Arguenon et al., 2006; Hao et al., 2004; Noguchi et al., 2004).

Even if the workspace is well defined, safety is an important factor that affects the fleet composition. The vehicles should be in frequent communication with the external computer to provide data about current status and operation, and a human operator must be in constant supervision. The operator must be present at some instants: mission configuration, mission start, mission stop or suspension, among others. Thus, an operator interface is essential.

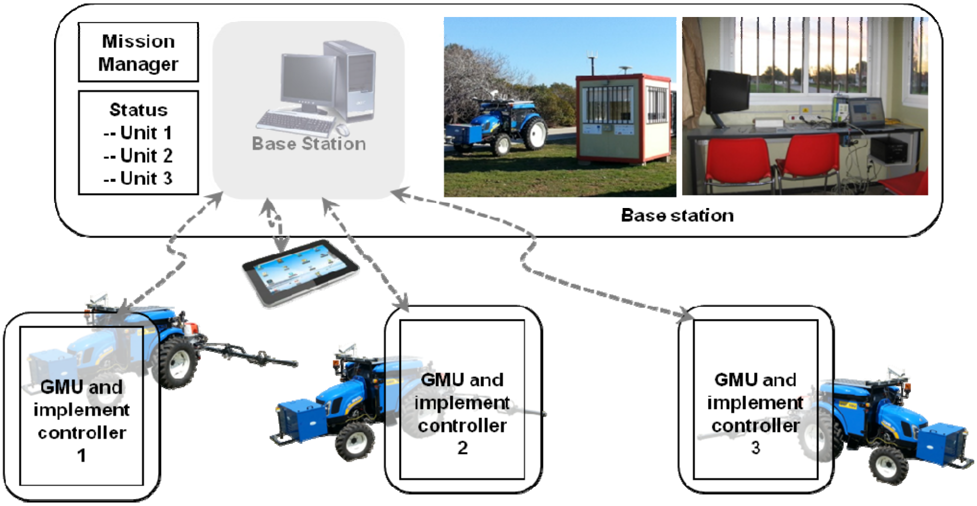


Figure 4.4. General schema of the fleet of robot topology for the RHEA project.

Based on these requirements, the topology of the fleet of robots defined for the RHEA project was a central-external computer located in a Base Station (BS) for planning, supervising, and allowing the user to access a full interface, in addition to a user portable device (UPD) that allows the user to approach the units to maintain control and supervision of the fleet (See Figure 4.4). In this topology, a master external computer connected to the fleet units through a wireless communication system runs a mission manager (mission planner and mission supervisor) that sends commands to (and receives data from) the fleet mobile units.

4.4. Implementation of the Proposed Main Controller: The Evolution of the RHEA Computing System

The computing system onboard the mobile units must communicate with a large number of subsystems, such as those specified in Chapter 2, which are based on computers running different operating systems (e.g., Windows, Linux, QNX) and software modules developed in different languages (C++, .NET, Python, etc.). The first solution was to connect all subsystems through an Ethernet network through a switch and use a computer as a central controller (Hinterhofer et al., 2011). This initial solution is depicted in Figure 4.5. The Main Controller is connected to the peripherals through either a serial line or an Ethernet network (802.3 Local Area

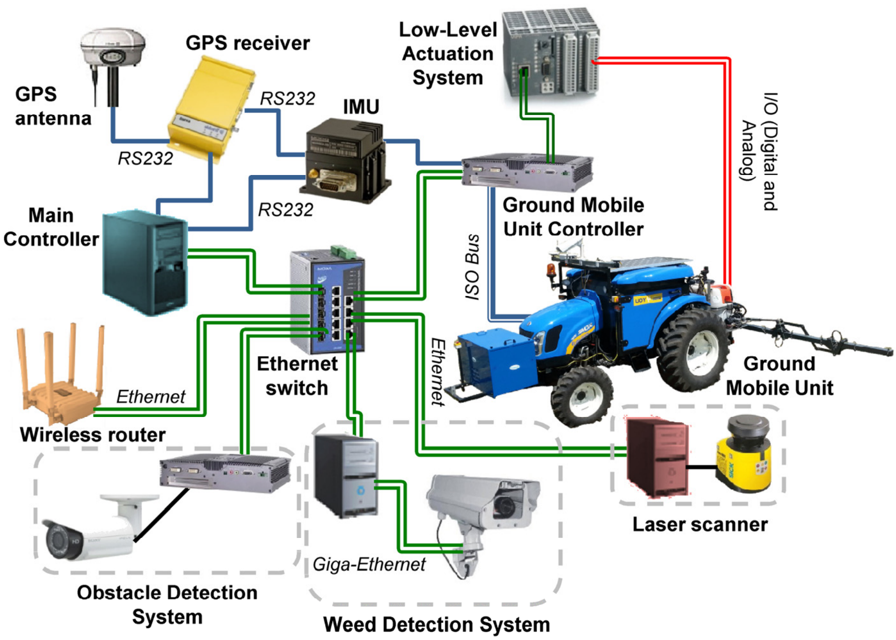


Figure 4.5. General scheme of the hardware architecture for the autonomous mobile robot in the RHEA project.

Network) via an Ethernet switch, which requires a Network Manager running on a computer connected to the Ethernet Switch, normally the Main Controller.

The first step toward centralization consisted of integrating the Weed Detection System (WDS) into the Main Controller. The vision camera is GigE Vision standard compliant (global camera interface standard developed using the Gigabit Ethernet communication protocol framework for transmitting high-speed video and related control data), and the Main Controller has two Gigabit Ethernet ports. This allows for a direct interface between the camera and the Main Controller using the functionalities provided by LabVIEW for configuration and acquisition, avoiding the development of new drivers and eliminating the vision computer. This solution is illustrated in Figure 4.6.

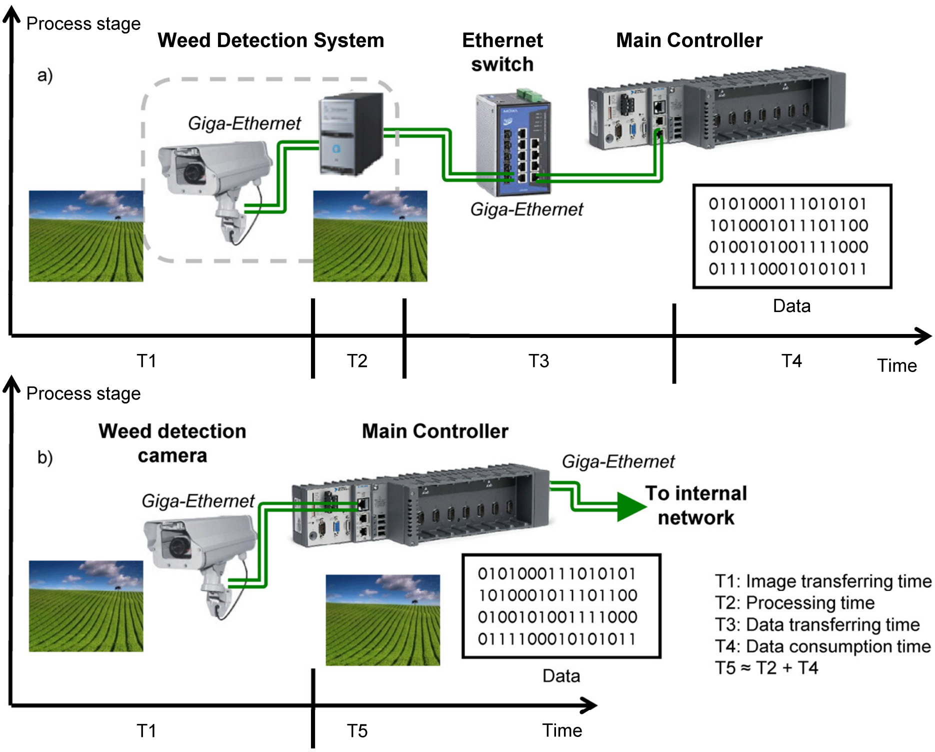


Figure 4.6. Comparison of the distributed approach (a) and the centralized approach (b) in the Weed Detection system regarding the use of resources, information availability and communication time.

Two major problems arose at that time. The first was reusing the acquisition software implemented in C++; the second was to assess the Main Controller running the vision algorithms as an additional load. The first problem was solved by using the LabVIEW connectivity with third-party tools, which allows the programmers to call external scientific libraries in the form of C code, DLLs (Dynamically Linked Library) and code interface nodes (CINs), which include C code compiled into LabVIEW nodes. The specific solution consisted of converting the vision code developed in the C++ language for Windows 7 into a DLL (See Figure 4.7). This DLL can be loaded into the Main Controller and its functions called from LabVIEW. One of the important steps in creating a compatible DLL is the detection and substitution of pieces of code that may have problems during the execution, such as system calls. This problem can occur when an external code developed for other operating systems (in this case Windows 7) is called by the LabVIEW

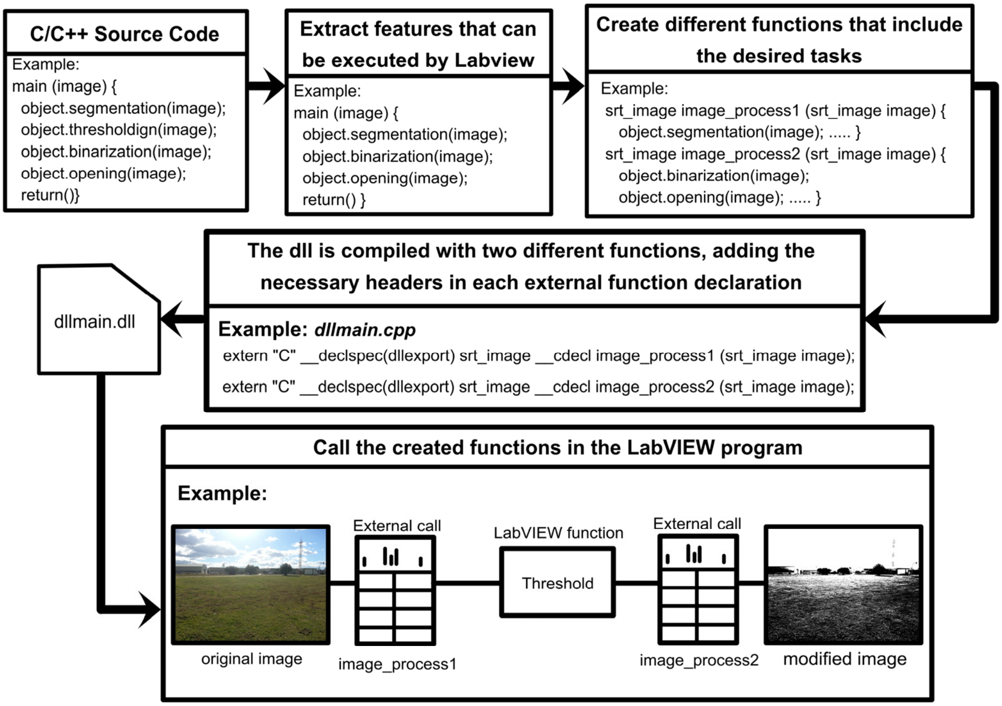


Figure 4.7. Example of the procedure for calling external code in LabVIEW using DLLs.

Real-Time Operative System (LabVIEW RTOS) and attempts to access some kernel libraries. This may generate conflicts, and therefore it is recommended that this practice be avoided as much as possible. Once the source code is adapted for execution in the LabVIEW RTOS, it must be packaged in one or different C language functions following the procedure defined in Figure 4.7.

There are several advantages of running the real-time features of the algorithms in the same computer (See Figure 4.6):

1. By eliminating the vision computer (WDS computer) and implementing the execution of the weed detection task in the Main Controller, the deterministic performance is increased, which removes an intermediate non-real-time OS (Windows) and an extra Ethernet network link.

2. By receiving the information directly from the camera, other processes that are being executed in the Main Controller can rapidly access the images by sharing the same memory space.

3. By integrating the acquisition and processing algorithms in the Main Controller, the information about the weed distribution is rapidly shared with other processes that require it, which decreases the communication time and increases the real-time response. While this integration generates a problem of interprocess communication by shared memory, it is compensated (in this particular case) by eliminating the communication between different machines. Because there is no need to share images with other computers, the development of drivers for these tasks is eliminated.

A second strategy to improve the centralization of the RHEA system is to unify the two vision systems: the Weed Detection System (WDS) and the Obstacle Detection System (ODS), integrated in the full system. Both systems use similar image-capture mechanisms and image-processing algorithms, which can be integrated into the same computer to save hardware resources. The software, which is written in the C++ language for the Linux operating system, is converted to a DLL following the procedure described for the WDS (See Figure 4.7). The main problem with this configuration is the lack of real parallelism in the execution of the algorithms, which increases the computing time. However, this increase is compensated by the elimination of the delay in the information flow from the ODS to the Main Controller through the Ethernet. Analogously to the integration process of the WDS into the Main Controller, Figure 4.6 shows that, in the proposed architecture, the time T3 will be eliminated in the data flow of the ODS in comparison with the original schema. In the proposed architecture, the camera acquires an image and sends it via the Ethernet to the Main Controller in charge of both processing the image and making the decision. By contrast, with the original schema, the ODS information must pass through more network elements, increasing transmission time.

Some advantages of integrating the two vision systems are as follows:

1. The application requires only one camera, which reduces the amount of hardware and relevant equipment (the vision fields of both cameras are similar);
2. The Main Controller allocates the same memory space to share information between the two vision process (which can take advantage of the processed image to be used by the two different processes); and
3. The two processes can be executed in parallel.

One of the further developments and benefits of this integration is the improvement of the performance in an obstacle-detection task in real-time applications by fusing the camera and the laser information. Integrating the sensor acquisition methods and the fusion method in the same computer increases the reliability of deadline compliance, data correlation, and synchronization compared to the original scheme. However, if the data acquisition, both with the camera and the laser, is not performed on the decision-making computer, the non-deterministic features of the Ethernet will reduce the real-time capabilities, expanding the timeframe, and producing synchronization problems.

These are two examples of possible system centralization of complex subsystems; however, other subsystems can be centralized in a simpler way by using the plug-and-play features (e.g., Ethernet communication through wireless local area network (WLAN) modules and switches; Laser and Inertial Measurement Units through RS-232 serial modules, industrial communication buses through CAN bus and; ISO modules, Low-Level Actuation System through analog and digital I/O modules; etc.). Figure 4.8 shows the final system scheme, which includes the main external sensorial components.

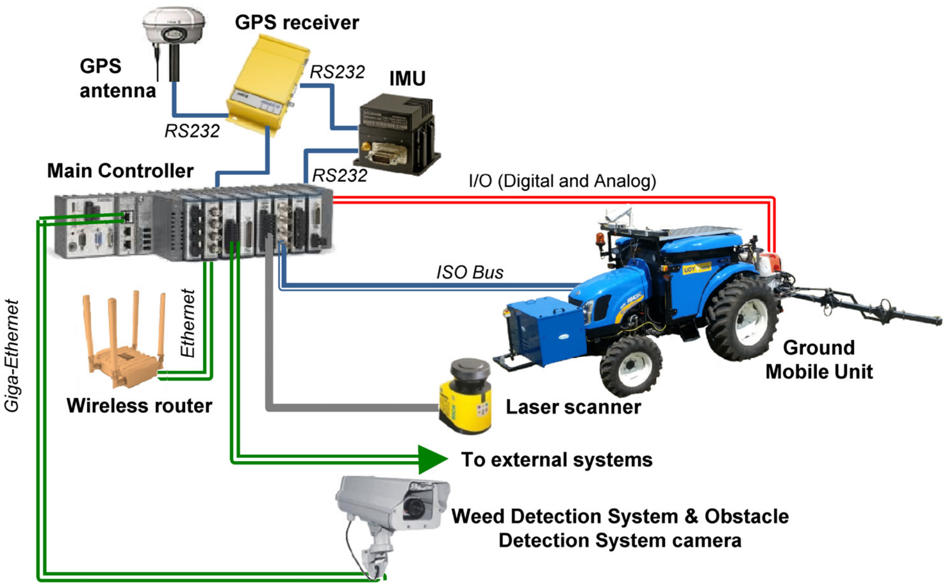


Figure 4.8. Prospective hardware configuration of the RHEA system.

Using this basic controller and taking advantage of the LabVIEW features, we have defined a simple software architecture to connect all subsystems to the main module in charge of making decisions, named the High-Level Decision-Making System (HLDMS) in the RHEA project. Figure 4.9 illustrates a general schematic diagram in which the following three different software levels are defined:

1. The first level, represented by yellow boxes, consists of driver modules that allow communication with the various sensors, actuators, and other elements of the system (e.g., external user interface).
2. The second level, represented by blue boxes, consists of several modules in charge of interpreting, generating and/or merging information from the lowest level to make it more accessible to the decision-making system module or to adjust control parameters for guidance and actuation.
3. In the highest control level, represented by the red box, the decision-making algorithm takes the information from the lower-level modules, and based on the desired behavior of the fully autonomous agricultural system, a plan to be executed by the guidance control and the treatment application is formulated.

After minimizing the hardware of the individual mobile units, the next step is to minimize the hardware of the whole fleet. The procedure of minimizing the hardware of a fleet of robots relies on the other elements that constitute the fleet of robots: the base station and the operator. As indicated in previous sections, the operator must be present at some instants of the application to configure and supervise the mission. Thus, an operator interface is essential, which can be provided in the form of a base station (computer monitor and keyboard) or a portable device (e.g., tablet, Smartphone) that allows the operator to move close to the mobile units. A step forward in the configuration of the fleet of robots would be to structure a fully unmanned fleet with no operator intervention. This prospective case, which is not currently allowed by the legislation of many countries, would dispense with the base station, and the mission manager and the fleet supervisor would be run in the computing system of the mobile units. Two solutions are envisaged:

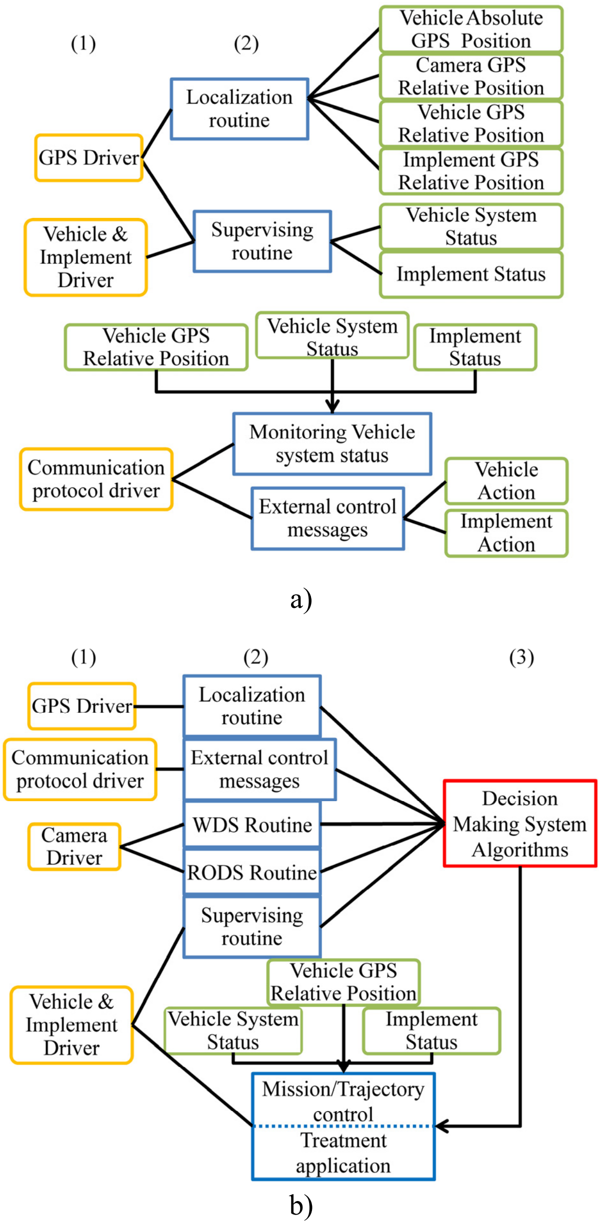


Figure 4.9. General diagram of the High-level Decision-Making System indicating three levels of main subsystems, their outputs and their interactions with other subsystems. a) Principal outputs (green boxes) of the lower subsystems. b) Flow between sensory systems and control systems and navigation process execution.

4.4.1. Master-Slave Configuration

One fleet unit controller acts as a master running the mission manager and the supervisor of the fleet, while the rest act as slaves receiving commands and returning data. A failure in this master controller also stops the mission of the fleet, but the likelihood of failure decreases because the whole fleet has one less computer and communication system (See Figure 4.10) with respect to the central-external controller solution. Adaptation to this topology is straightforward: the mission manager algorithms running on the Base Station computer can be packaged into a DLL and included, with minor software modifications, in a Main Controller, which will act as the fleet master controller. This process is the one explained in Figure 4.7.

Besides reducing hardware and structural elements in the fleet of robots, another advantage of this topology is the extension of the working area of the fleet. If the mission supervisor is fixed at a point in the field, the maximum working range of each unit is limited by the range of the communication system. A typical wireless network can have an open field range of up to 150 meters. As indicated in previous sections, the use of a fleet of autonomous robots in agriculture may be feasible in extensive applications that require long hours of continuous working in fields of tens of hectares. Thus, a larger communication range is required. One solution is the use of larger antennas and increasing the power of the transmitter/receiver to maintain an acceptable bandwidth or the use of signal repeaters. However, as there is a master unit in this topology, the mission supervisor has the ability to move around the field, which increases the working area of the entire fleet (maintaining a typical wireless network configuration), as long as the mission is defined so that each unit is within communication range.

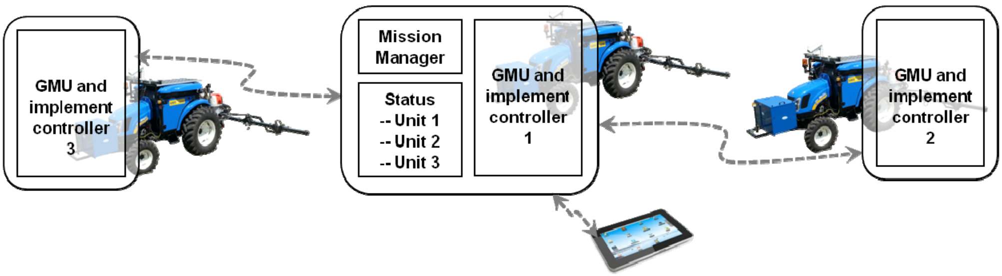


Figure 4.10. Master-slave configuration.

4.4.2. Immerse Configuration

The mission manager is copied in all mobile unit controllers so that a failure in one unit means that unit stops, while the rest can reconfigure the mission plan to accomplish the task. Note that the hardware is not increased and that the same mission manager algorithms run on every unit controller (See Figure 4.11), while the unit statuses are shared among all the robots by broadcasting a few status data in a sampling period basis. When a unit goes out of order, the others receive that information in the status or by a sampling period timeout; in such a case, the remaining active units will compute the mission manager, taking into account that incidence.

For this solution, there is not a clear gain of hardware reduction in the general architecture, but the immerse controller increases the robustness of the system by using a mirrored mission planner on each mobile unit controller. This immerse controller allows each mobile unit to supervise (mission supervisor) the execution of the plan and monitor the status (position, speed, etc.) of the other mobile units while adapting the missions of individual units to meet the goal of the fleet. This configuration, which is illustrated in Figure 4.11, is well suited to the hardware architecture presented in Section 4.4 for the ground mobile unit, in which the use of a cRIO system as the Main Controller permits direct communication with others cRIO systems without the development of drivers and communication protocols,

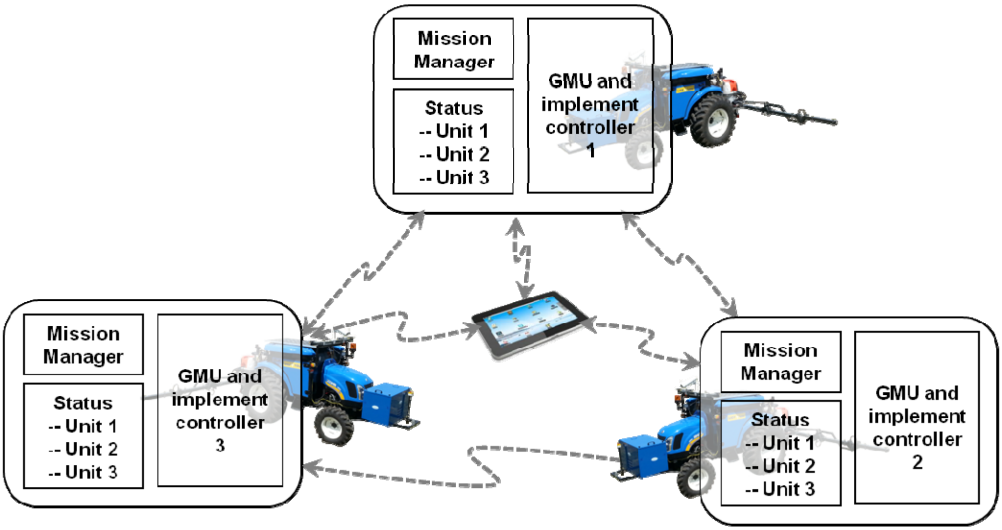


Figure 4.11. Immerse configuration.

thanks to the ability of the LabVIEW utilities to share information between NI systems.

4.5. Results

To present the implementation of a working fleet of robots configured with the Main Controller integrated in the proposed architecture, a set of assessments was conducted in a real experimental field as part of the RHEA project (Gonzalez-de-Santos et al., 2012). Several tests and integrations have been conducted that have positively assessed the system efficiency and ease of new integrations, which are organized as follow: Subsections 4.5.1 and 4.5.2 present both quantitative and qualitative results associated with both hardware element reduction and software development minimization in a single, fully autonomous agricultural system; Subsection 4.5.3 presents the results of an algorithm for collision avoidance, allowing the assessment of the benefit of hardware reduction in a fleet of robots oriented to agriculture.

4.5.1. Integration of the Weed Detection System in the Main Controller

The first assessment trial was focused on evaluating both the image acquisition and processing procedure of the Weed Detection System by using the proposed architecture (See Figure 4.8) and compared them with those obtained with the original RHEA scheme (See Figure 4.5). The algorithms used for the image processing were those developed by Guerrero et al. (2012) and Montalvo et al. (2012). For that trial, we measured the time required for each topology (centralized vs. distributed) to acquire an image and generate an output, which was received in the Main Controller (See Table 4.1). In the first trial (with the original scheme), the computer was exclusively dedicated to image acquisition and image processing tasks. However, using the proposed architecture, image acquisition, image processing, and four additional tasks defined in Table 4.1 were executed in parallel, meeting the scheduled time. Considering that each topology generates very similar results, we can conclude that we have maintained the required performance of the system, decreasing hardware and developing a small number of communication interfaces. Furthermore, the image acquired by the Weed Detection System is available within the Main Controller in half the time using the architecture illustrated in Figure 4.8 compared to the original scheme (See Figure 4.5). Because the images are high resolution, this time is quite significant when performing real-time calculations, and thus the same image can be shared with other processes, such as the Obstacle Detection System, avoiding redundant hardware (several cameras, for instance).

Table 4.1. Comparative timing results between the RHEA original schema and the proposed architecture regarding the Weed Detection System.

Time required	Image Acquisition	Fps acquired	Image Processing	Fps processed	Image Sharing	Other process running
Original structure	75 - 150 ms	5	150 - 250 ms	4	150 - 200 ms	0
Proposed structure	80 - 160 ms	5	200 - 250 ms	4	1 ms	4 (See table below for process description)

Other process running	Scheduled periods
Path following supervising routine	100 ms
Steering and throttle control routine	10 ms
Telemetry routine	100 ms
Localization routine	100 ms

4.5.2. Integration of the Ground Mobile Unit Controller in the Main Controller

One more evaluation of the system was performed by removing the Ground Mobile Unit Controller (GMUC) in charge of the vehicle guidance and implementing path follower algorithms in the Main Controller. In this case, we evaluated the system capabilities to react to changes in both the trajectory and speed of the vehicle, which were measured as the number of messages sent to control both the vehicle speed and steering. Leaving aside the vehicle mechanical response and the performance of the path-following algorithms, by using the original RHEA scheme, the Main Controller can send messages (new trajectories) at a rate of 6–10 Hz. However, by using the proposed architecture, the Main Controller can send messages (new steering and speed references values) at a rate of 100 Hz. It is not correct to directly compare these two values because the messages correspond to diverse control levels. Therefore, a qualitative analysis must be performed. The original RHEA scheme defines the guidance system as a deliberative architecture in which the trajectory planning is performed by the Main Controller (based on a predefined mission and information of the perception system) and the GMUC executes that plan. The proposed architecture changes this configuration into a hybrid architecture, where, in critical situations (e.g., obstacle avoidance, row guidance, safety procedures), the capabilities of changing the position and orientation of the vehicle are improved. Although the behaviors of these two schemes are well-known and have been studied for years (Brooks, 1986; Payton, 1986), they remain a current research topic (Nakhaeinia et al., 2011) and are well suited to the requirements defined in Section 4.3.

The implemented controller relies on a fuzzy logic algorithm presented in Chapter 3, Section 3.6.

4.5.3. Implementation of a Collision Avoidance Algorithm in the RHEA Fleet of Robots

As a final test to validate the use of the proposed architecture in a fleet of robots oriented to agricultural tasks, the implementation of a method for avoiding collisions between units was evaluated. The fleet configuration was as follows:

1. Regarding each individual, fully autonomous agricultural system, the positioning system (RTK-GPS) was the only sensory element enabled for this test, in addition to the communication system (wireless communication) and the Main Controller (in charge of executing the mission and communicating with both the user and the mission supervisor).
2. The fleet topology used in these tests was the master-slave configuration (See Figure 4.9), in which the algorithms to configure and transmit the mission to each unit, in addition to the fleet supervisor algorithm, were executed within the Main Controller on-board the ground mobile unit one (GMU1). These algorithms had a built-in user interface (See Figure 4.12) that could be accessed remotely by the user via an external computer connected to the network of the fleet. With this interface the user can: a) monitor the status and location of each unit; b) load a predefined mission to each unit; c) record the GPS relative position of each unit; and d) start, stop or pause the motion of each unit, among other actions.

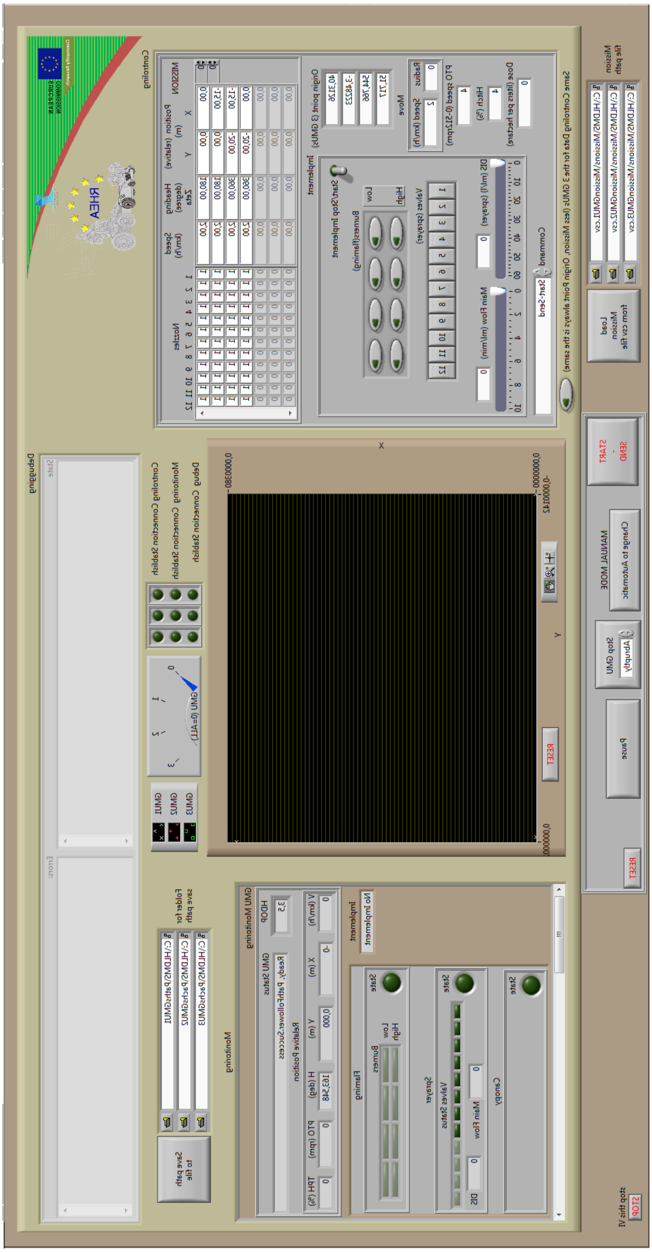


Figure 4.12. Snapshoot of the user interface for controlling and monitoring the fleet of robots.

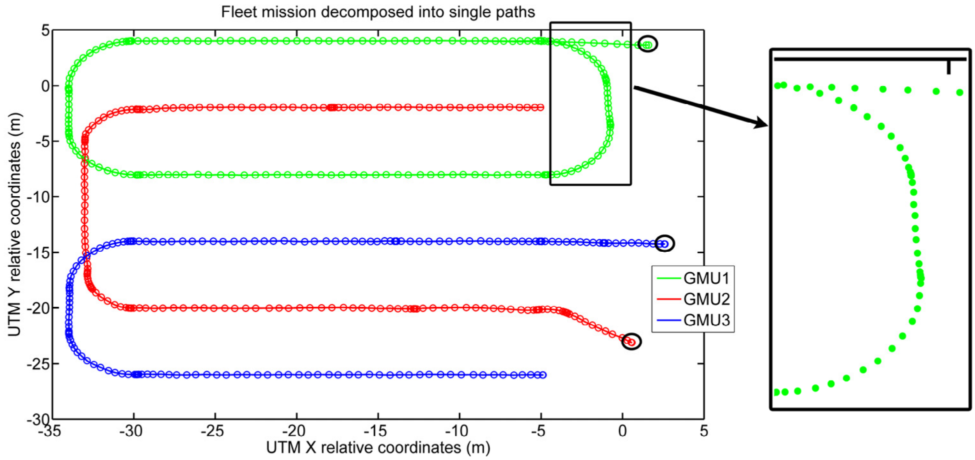
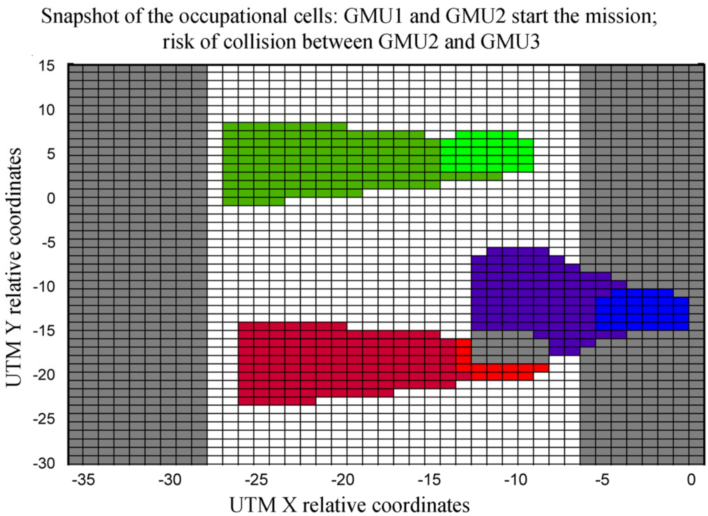


Figure 4.13. GPS position recorded for each unit representing the mission execution. The black circles represent the origin point of each unit.

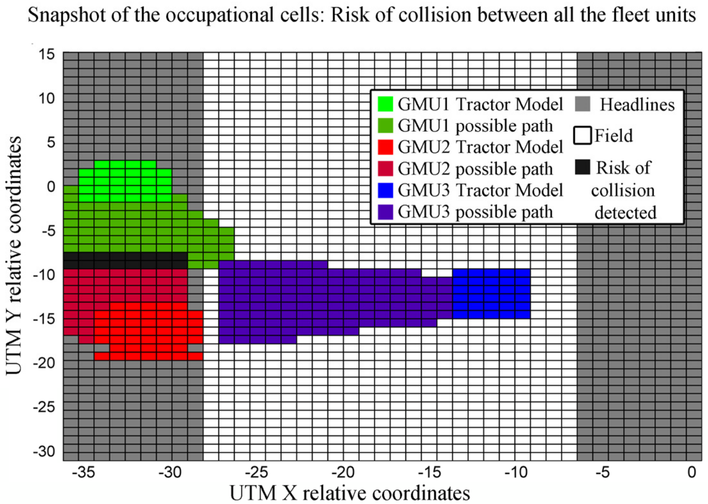
Each unit must follow a user-predefined path at a constant speed. Each path consists of crossing a real field (35 meter long by 25 meter wide), making a U-shape turn, and returning down the field on a different crop line. The units are allowed to make the turns in an area with a length of approximately 8 meters at the headlines. The GPS positions recorded by each unit and the general mission sent to the fleet of robots are illustrated in Figure 4.13.

Higher concentrations of GPS positions in the figure (the colored circles for each unit) indicate that the unit was moving at low speed or even stopped; by contrast, a lower concentration of GPS positions corresponds to normal development of the sub-mission: following a predefined path at a constant speed.

Although the fleet mission can be defined as optimal both in time and space (because the characteristics of the field and the fleet are well known), it is possible to identify random external elements that alter the planned development of the mission and generate potential collision situations accordingly. Examples of these situations include the following: a) detection of moving obstacles (e.g., persons, animals, other tractors); b) treatment parameters that affect the speed of operation (e.g., in a weed control treatment in which a decrease in speed is required for a more optimal application); c) small temporary failures in the system itself (e.g., loss or decrease of the accuracy of the GPS signal, wireless communication loss). To avoid collisions between units, the fleet supervisor algorithm contains a procedure that receives the GPS positions of each unit and calculates their possible location in subsequent time instants based upon their intended movement (current heading).



a)



b)

Figure 4.14. Snapshots of the occupancy grid mapping for collision detection. a) Results of the collision detection within 10 seconds of the execution time of the mission. b) Results of the collision detection within 25 seconds of the execution time of the mission.

The collision avoidance algorithm models each tractor as a square element, and its intended motion as a conic section in which the vertex of the cone is in the center of each tractor. The opening angle of the conic section depends on whether the tractor is inside the field (smaller angle) or in the headlines (bigger angle), given that inside the field each tractor normally moves along a straight line. The fleet supervisor assigns priorities for each unit to continue its sub-mission or stop until the risk of collision disappears. For this particular case, GMU1 has the highest priority, while GMU3 has the lower priority. The method for detecting potential collisions is occupancy grid mapping (See Figure 4.14).

Figure 4.15 illustrates the distance traveled by each fleet unit as a function of time. At some times (e.g., in the first 20 seconds of the mission; between the second 25 and 40 seconds), some units remain stopped because the fleet supervisor paused the execution of the sub-mission of these units because there was a potential collision situation. Figure 4.14(a) shows the result of the collision detection algorithm for an instant of time between the first 20 seconds of the general mission, during which a possible collision between GMU2 and GMU3 is present, and thus GMU3 will take longer to get to the other end of the field. This is the situation presented in Figure 4.14(b), in which GMU1 and GMU2 are making the turn to

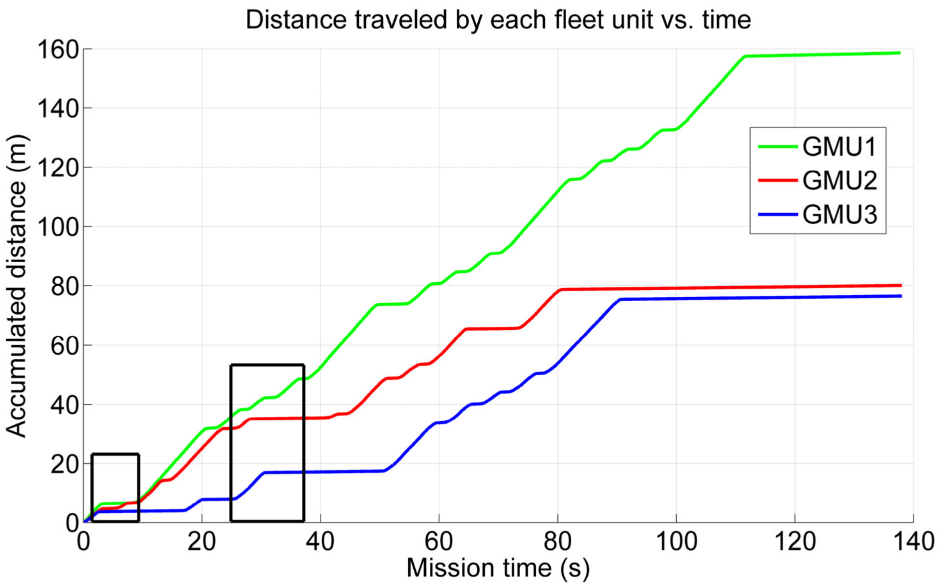


Figure 4.15. Accumulated distance traveled by each fleet unit as a function of the mission time.

return to the field and another possible collision situation is present. In this situation, the fleet supervisor allows GMU1 to continue with its sub-mission while stopping the movement of GMU2 until the collision situation disappears. In addition to the tests conducted for collision avoidance using the master-slave configuration, tests were performed with the original RHEA project configuration (See Figure 4.4), and as expected, the same results were obtained. These results confirm the potential of the proposed control architecture for an autonomous fleet of robots to allow hardware and software development reduction while maintaining the desired performance.

A video of the RHEA fleet is available at (RHEA_Fleet, 2014); the video includes images of the user interface described in Subsection 4.5.3 as well as a real-time result of the collision avoidance algorithm.

4.6. Conclusions

Robotics and new technologies have begun to improve common practices in agriculture, such as increasing yield performance and decreasing the use of chemicals that may affect the environment. Furthermore, new robotics systems for application in agriculture are under development to permit the integration of different technologies while enabling modularity, flexibility, and adaptability.

This chapter presents a structure for agricultural vehicles to work both independently and in fleets that is simple, robust, and reliable. The general scheme exhibits advantageous features to quickly implement new vehicle controllers and develop/integrate advanced agricultural implements. Three examples are reported herein: a patch sprayer, a machine for physical weed control, and an airblast sprayer.

The proposed architecture for the centralization of the Main Controller and the principal sensory systems provides advantages for a future sensor fusion. Integrating critical sensors in autonomous agricultural applications, such as high-definition cameras and lasers systems, allows the information to be merged to improve the performance of the sensory system in terms of greater accuracy, greater robustness, and increased complementary data and to reduce the amount of hardware, which increases the communication speed and the information shared by different modules.

In addition, in an autonomous agricultural application, when the environment exhibits changing light, soil, and crop characteristics, among others characteristics, the sensory system is required to perform more complex tasks, which consequently leads to the problem of overcharging the Main Controller due to both the execution of multiple tasks in the same controller and the high consumption of resources for sensory fusion tasks. Nevertheless, in the proposed solution, this overuse is compensated by the Main Controller characteristics and its ability to execute diverse processes in parallel and in real-time as well as the possibility of implementing very specific and time-critical operations in the FPGA device.

This proposal allows the robustness of autonomous agriculture robots and fleets of robots to be increased by reducing the equipment hardware onboard the mobile units and facilitating the integration of different sensors devices and software modules developed by professionals in different fields and skills. Moreover, minimizing user involvement in monitoring and safety functions and enabling the same elements of the fleet to manage certain critical situations can also permit the reduction of the amount of hardware and structural elements in the fleet, which might increase the working area of the entire fleet.

The system is operational, and both individual and fleet robot features have been tested. The previous section illustrates two examples of subsystem integration into the main controller regarding the vision system and the vehicle controller, indicating quantitative features (See Table 4.1 and Subsection 4.5.2). Moreover, algorithms to allow the robots in the fleet to collaborate, follow a plan, and avoid collisions between robots by using the master-slave configuration have been presented in Subsection 4.5.3. In general, the proposed system has been assessed as very efficient to easily integrate new sensors, implements, and innovative algorithms in a fleet of agricultural robots.

The industrial exploitation of the fully unmanned fleet concepts presented in this Thesis is not yet permitted by the legislation of most countries. Nevertheless, the use of autonomous vehicles on public roads is under consideration in Japan, Sweden, and several states in the USA, and autonomous cars will unquestionably be allowed everywhere in the near future. In any case, the authorization of autonomous vehicles for closed scenarios such as farms will definitely occur first.

Chapter 5

Integrating Subsystems in the Control Architecture: a Case Study of a Real Precision Agriculture Application

5.1. Introduction

As presented in previous chapters, a fully autonomous agricultural system consists of a set of diverse subsystems that allows it to perceive the environment, to be located and to move around a crop field, to communicate with others vehicles or users, and to perform the treatment. This chapter presents an integration of a perception, an actuation and a decision making as subsystems of the RHEA ground mobile unit (See Figure 5.1), taking as base the control architecture presented in Chapter 4 as well as the proposed approaches for the integration of a fully autonomous agricultural system working in a fleet of robots. An evaluation of each subsystems working in an agricultural robot as well as its integration have been performed in a real scenario. The proposed experiments had been carried out for a weed control application in maize fields (Frasconi et al., 2014; Peruzzi et al., 2012), but these results will allow the assessment of the proposed architecture also for other agricultural purposes such as cereal treatments or even for seeding, using the same vehicle with its architecture.

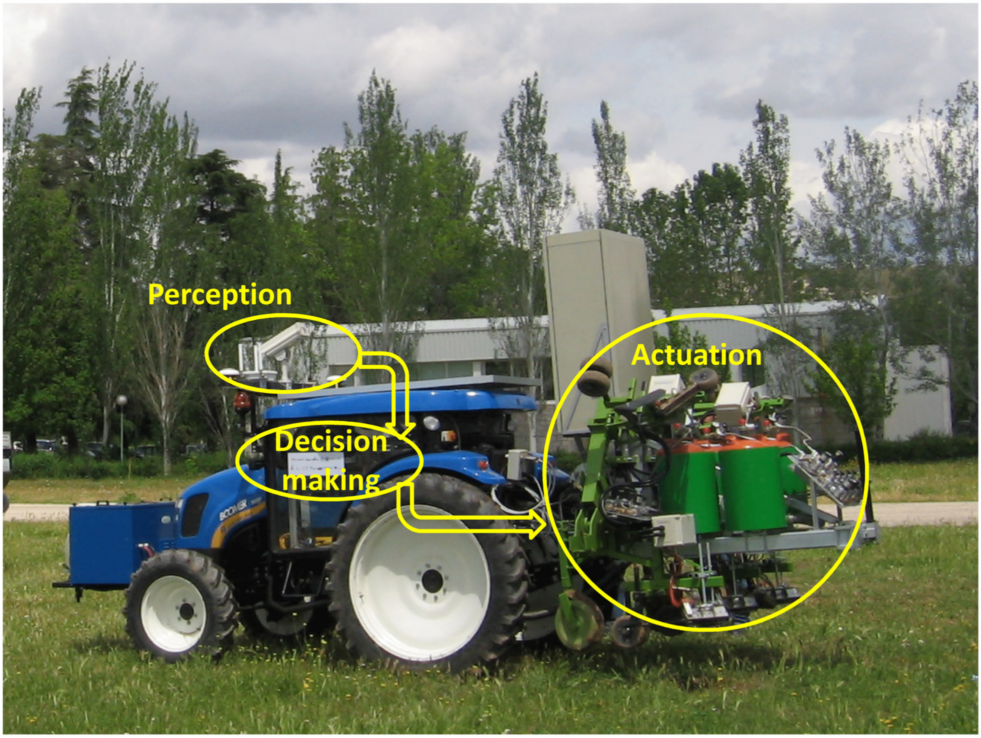


Figure 5.1. Perception, decision making, and actuation in an agricultural vehicle.

To accomplish these overall goals (objectives 1, 2, 3, and 7, Section 1.3), this chapter is organized as follows: Section 5.2 presents the description of the perception system that relies on machine vision. Its main tasks are row identification and weed detection. Section 5.3 briefly describes the actuation system. Then, the integration of the perception and actuation as well as the decision-making mechanisms are explained in Section 5.4. Experiments have been conducted in a real maize field with an autonomous vehicle that is a part of the RHEA project in which the subsystems introduced in this chapter are integrated; Section 5.5 details those experiments and discusses some results. The conclusions are finally drawn in Section 5.6. The proposal made in this chapter is a fundamental part of the work of Emmi et al. (2014a).

5.2. Perception System: Localization and Weed Detection

The perception system is designed for crop/weed identification with two main goals: row following and weed discrimination for site-specific treatment. Crop row detection is the basis for both weed discrimination and guidance and requires the localization and identification of the rows (straight line equations) in the image. This section is devoted to the specification of the perception system, the steps for data processing, and the properties of the system architecture.

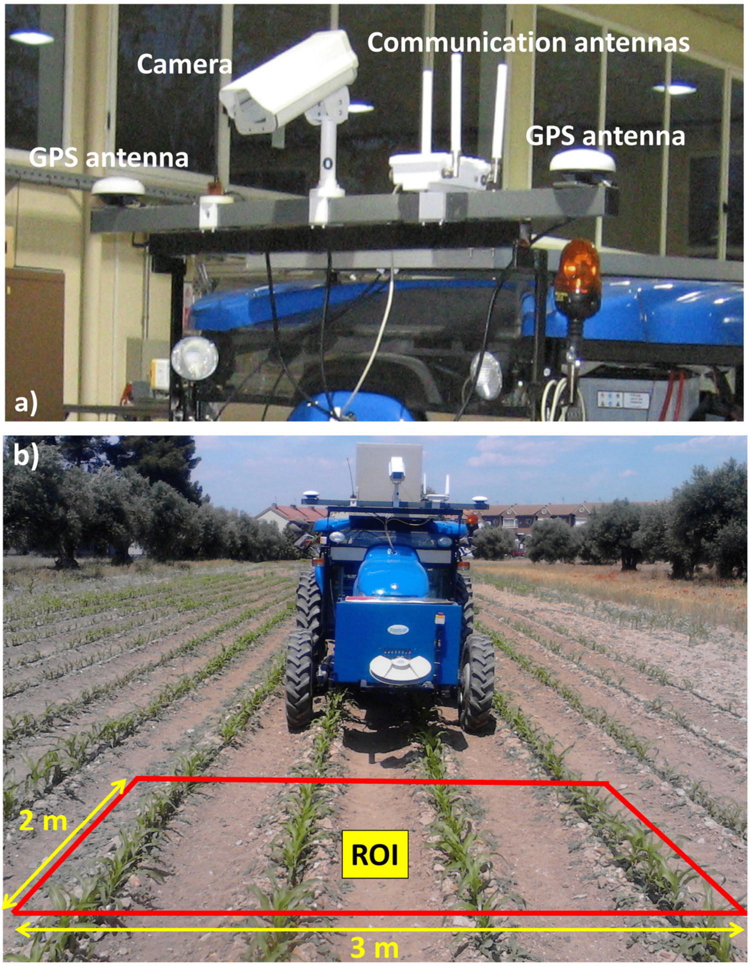


Figure 5.2. (a) Sensors on-board the tractor. (b) Region of Interest (ROI) for the vision system.

5.2.1. Description of the Perception System

The perception system consists of three main sensors: camera-based, IMU, and RTK-GPS (consisting of two antennas: one for XYZ positioning and the other for heading calculations) (Carballido et al., 2014). Figure 5.2(a) displays the main sensors on-board the autonomous vehicle (a GMU of the RHEA project). The camera and IMU are embedded into a housing with a fan controlled by a thermostat for cooling purposes, assuming that some agricultural tasks are conducted under high working temperatures, above 50 ºC. The housing is IP65 protected to work in harsh environments (exposure to dust, drops of liquid from patch sprayers, etc.). Additional to the appointed sensors, the perception system also comprises a wireless communication device, to enable the user for remotely controlling and monitoring the entire system. Figure 5.3 displays these parts assembled.

The camera-based sensor is the SVS4050CFLGEA model from SVS-VISTEK (2014) and is built with the CCD Kodak KAI 04050M/C sensor with a GR Bayer color filter; its resolution is 2,336 by 1,752 pixels with a 5.5 by 5.5 µm pixel size. This camera is Gigabit Ethernet compliant and it is connected to the Main Controller (See Section 5.4). The IMU (See Figure 5.3) of LORD MicroStrain® Sensing Systems (Williston, VT,, USA) is a 3DM-GX3® -35 high-performance model miniature Attitude Heading Reference System (AHRS) with GPS (MicroStrain,

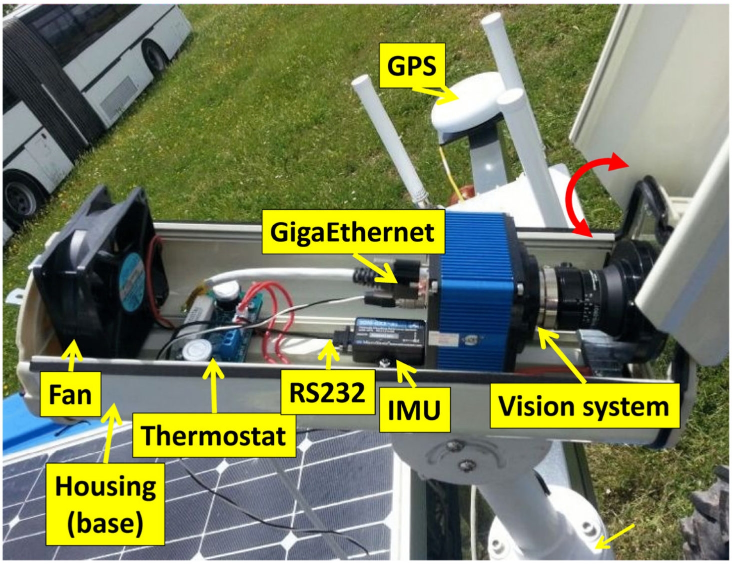


Figure 5.3. Perception system: sensors and equipment.

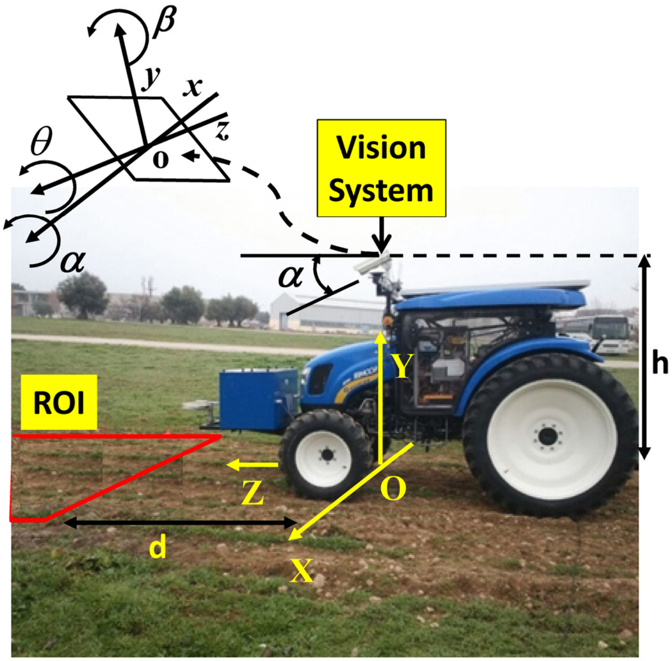


Figure 5.4. Camera system geometry.

2014). It is connected via RS232 to the Main Controller and provides information about pitch and roll angles. Both the camera and IMU are robust enough and exhibit sufficient capabilities for real-time performance, required for agricultural tasks. The goal is to apply specific treatments in the Region of Interest (ROI) in front of the tractor, which is a rectangular area 3 m wide and 2 m long (See Figure 5.2(b)). It covers four crop rows in the field. This area starts at 3 m with respect to a virtual vertical axis traversing the center of the image plane in the camera, i.e., where the scene is imaged.

Figure 5.4 displays the camera system geometry (Romeo et al., 2013). *OXYZ* is the reference frame located in the ground with its axes oriented as displayed; *h* is the height from *O* to the origin o of the reference frame *oxyz* attached to the camera; roll (θ), pitch (α), and yaw (β) define the three degrees of freedom of the image plane with respect to the referential system; *d* is the distance from the beginning of the ROI to the *X* axis.

5.2.2. Characteristics of the Perception System

Four properties have been identified as basic requirements for the perception system integrated into the proposed architectural design:

a) Flexibility/modularity

The perception system consists of the elements described above with a direct communication link to the High-Level Decision-Making System (HLDMS) running on the Main Controller. Different sensors can be connected via GigaEthernet and RS232 communication ports, which are standard interfaces. Any sensor can be connected/disconnected without restrictions other than the physical capacity of the Main Controller (See Section 5.4). The operations of linkage and decoupling can be carried out via software, without affecting the remaining modules or the operability. This procedure allows a multi-sensor arrangement according to the required agricultural tasks. Some crop line detection algorithms do not need the IMU, and when this happens, this sensor is simply ignored and then activated when required. This method avoids important disruptions to the designed systems and at the same time proves the flexibility and modularity of the proposed architecture.

b) Scalability

Sensors and their corresponding drivers can be added to increase the amount of work according to the demanded agricultural tasks. Again, the unique restriction is the limitation of the number of ports available in the Main Controller, which can be easily expanded. So, we could add a multispectral or thermal camera for plant discrimination or a stereoscopic vision-based system with a GigaEthernet connection for object detection for safety purposes. Different cameras with higher resolutions are accepted when required. Regarding the processing of data provided by the sensors, the HLDMS implemented in the Main Controller allows for high-performance processing.

c) Robustness

The camera-based system is robust enough to support the adverse outdoor agricultural environments with sufficient physical and electronic protections. It is designed to withstand mechanical vibrations from the tractor's engine, soil roughness, extreme temperatures, and high variability in illumination. Additionally, the camera is equipped with an ultraviolet and infrared (UV/IR) filter to cut spectral ultraviolet and infrared radiation, which considerably affects the image quality. The IMU is encapsulated and calibrated to provide stable values.

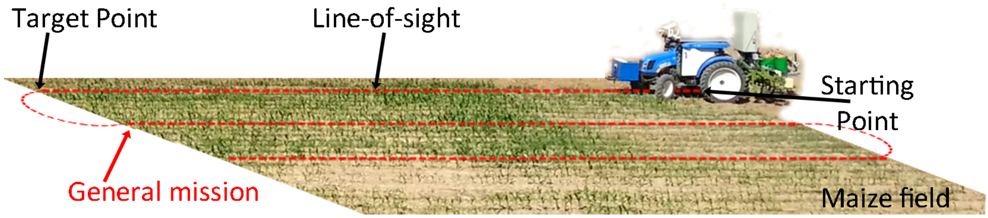


Figure 5.5. Example of path planning in the maize field.

d) Real-time/Performance

The perception system, particularly the camera, is arranged onboard the tractor to cover the region of interest where the specific actuation is to be applied. They are placed close to the center of gravity to minimize vibrations and undesired mechanical effects. The image acquisition is controlled through the exposure time, again with the aim of achieving high quality images. The data processing for crop/weed detection and guidance is designed under specific modules, programmed as dynamic-link libraries (DLL) in C++, and embedded in the Main Controller. The modules are optimized to work in real-time for the proposed specific treatment.

5.2.3. Process: Integration of Information

The vehicle is programmed to follow a pre-defined plan or general mission (See Figure 5.5). The mission consists of a set of waypoints that are established based on GPS coordinates, which define the beginning (starting points) and end positions (target points) for crossing the field. For this particular case, the information from the mission contains some uncertainty, so that the start and end points may not match the corresponding crop line's center. This requires the use of the crop row detection system to correct this uncertainty presented in the general mission.

In addition to the crop row detection, the perception system delivers information on the weed infestation in the field, allowing the computation of the percentage of weed presence inside the ROI. To do this, the ROI is divided into rectangular sections 0.375 m wide and 0.25 m long. The size of these sections is adjusted based on the characteristics of the actuation system that perform the treatment. The procedure is as follows:

1. The operation speed set for this type of treatment is defined as 0.83 m/s (3 km/h).
2. The pre-defined plan determines the traversal order of the waypoints to be visited, including starting and target points.
3. Between two waypoints inside the field, the vehicle follows the line-of-sight.
4. The camera captures images at frame rates up to ten images per second.
5. The system reads the GPS coordinates at a rate of 10 Hz and captures an image whenever the vehicle moves within 2 m on the field, which is the length of the ROI.
6. The camera vision system processes each image to identify four crop lines. The IMU provides information about extrinsic camera parameters, pitch (α) and roll (θ), so that, together with the remaining extrinsic and intrinsic parameters, four expected crop lines are identified. The expected crop lines serve as guidelines to determine the real crop lines (Romeo et al., 2013).
7. Based on the relative positioning of the two central crop lines identified with respect to the center of the image, if a deviation occur between the detected crop lines and the line-of-sight, the lateral deviation and heading are corrected to align the tractor with the real crop lines in the field.
8. The detected crop lines are used to determine the weed coverage inside the ROI, based on the green densities around the crop lines and between adjacent crop lines (Guerrero et al., 2013).

5.2.4. Geo-positioning Images

Because the raw image received from the camera is transmitted by Ethernet (non-deterministic procedure), the image analysis process consumes a specific amount of time and the actuation point (implement elements that perform the treatment) is located several meters behind the ROI, an element for synchronization and geo-positioning is needed to maintain a real-time performance and high-accuracy treatment. To accomplish this synchronization, each image captured is associated with a GPS position, and a map for weed coverage is created that is referenced to GPS coordinates.

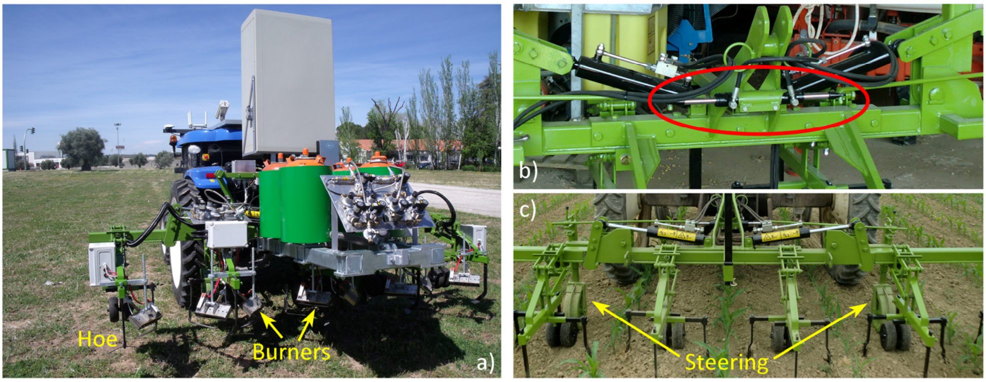


Figure 5.6. (a) Machine for physical weed control. (b) Implement steering actuator (implement front view). (c) Main frame (implement rear view).

5.3. Sensing/Actuating in Crops

Actuation in crops, which is the primary objective in agriculture, is normally performed by implements or devices towed/pulled by tractors that provide energy and motion. Implements are tools composed of simple sensors to obtain the status of the crop and simple actuators to perform simple actuation such as opening/closing valves, moving prismatic cylinders, etc. Most of these sensors/actuators are controlled by using PLCs or similar devices. If sophisticated sensor systems such as a machine-vision system or range finders are required, they are provided as external devices as indicated in Section 5.2.

5.3.1. Description of the Actuation System

Although the proposed system can be applied to a large number of implements, we will specify the system for a particular machine (Peruzzi et al., 2012), which is devoted for physical weed control (See Figure 5.6(a)) in flame-resistant crops such as maize, onion, garlic, etc. This implement is pulled by the autonomous tractor, and the Main Controller is in charge of decision making and synchronizing the activation of the treatment as well as managing the lateral position of the implement with respect to the vehicle's position.

This specific implement consists of four couples of burners attached to a main frame (See Figure 5.6(a)) to address four successive crop rows. The objective of the burners is to perform selective treatment in the intra-row space. The treatment in the inter-row space is achieved by mechanical actuation, i.e., specialized hoes (See Figure 5.6(a)). Every burner's flame intensity depends on the weed coverage identified by the weed detection system presented in Section 5.2 (Frasconi et al., 2012). The control of the ignition of the burners is performed by the Actuation Controller, which receives the action messages from the Main Controller.

Given that the implement contains two different elements to perform weed control, and given the possible risk of crop damage, an adequate degree of accuracy in positioning the burners and mechanical elements is needed. This step is performed by a guidance system, which is in charge of executing small adjustments in the lateral position of the implement with respect to the vehicle. This lateral positioning system consists of a linear actuator (central double rod hydraulic cylinder, See Figure 5.6(b)) that modifies the angle of the steering wheels, allowing the operative machine to move laterally with respect to the vehicle (See Figure 5.6(c)). This cylinder features a displacement of ±0.031 m, exerts a force of 2000 N, and is powered by the hydraulic system of the vehicle. The lateral control of the implement is performed directly by the Main Controller through the CAN bus communication system onboard the autonomous vehicle.

5.3.1.1. Lateral-Position Sensor

The positioning device for measuring the lateral displacement of the implement with respect to the vehicle is composed of a passive mechanism and a positioning sensor. The passive mechanism relies on a telescopic arm that joins the vehicle's rear to the implement main frame (See Figure 5.7(b)). The end of the arm is fixed to the vehicle through a passive rotary joint, with the rotation axis perpendicular to the arm. The other end is fixed to a carriage through a ball joint. The carriage can slide over a linear guide. A cable-pull potentiometer[1] is fixed to the carriage so that the sensor can measure the displacement of the implement. Thus, the positioning device measures the relative displacement of the implement with respect to the vehicle in a direction perpendicular to the vehicle's longitudinal axis. Figure 5.7(b) shows the basic scheme of the sensory system, and Figure 5.7(a) and Figure 5.7(c) illustrate how it is placed between the implement and the vehicle. In addition to the lateral-position sensor for measuring the displacement of the implement with respect

[1] Unimesure Inc., model JX-PA-20-N14-13S-125; http://www.unimeasure.com/

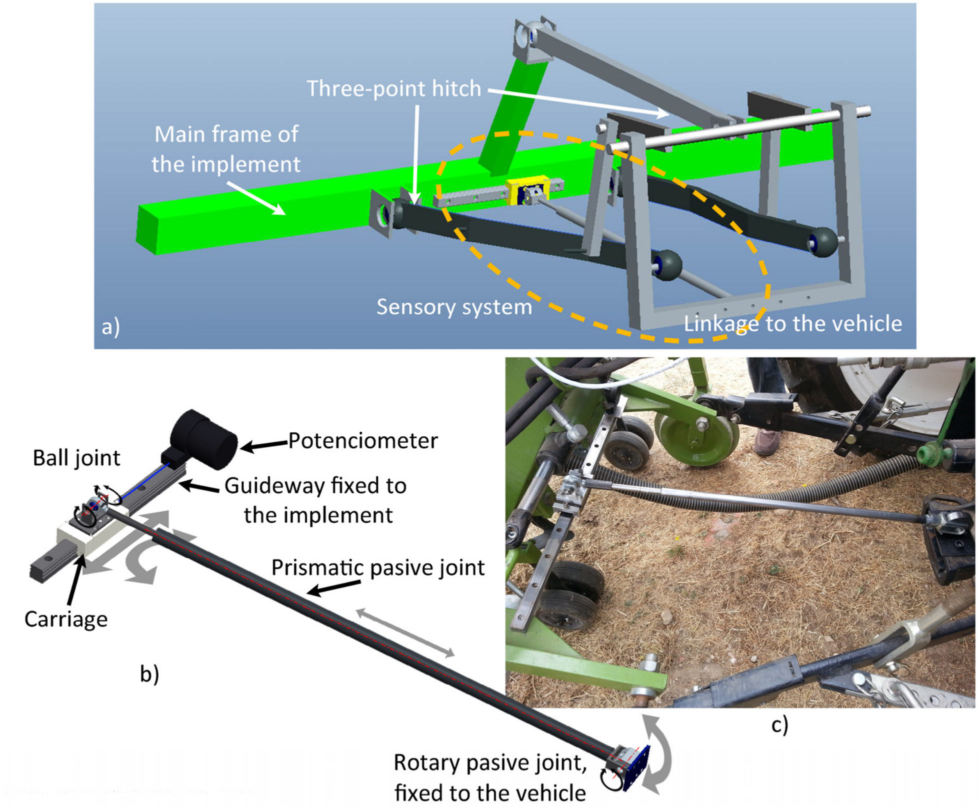


Figure 5.7. Lateral-position sensor setup. (a) Assembly diagram of the sensory system between the implement and the vehicle. (b) Structure of the sensory system. (c) Photo of actual sensory system.

to the vehicle, an encoder[1] was placed in the hydraulic cylinder that modifies the angle of the steering wheels for more precise control of the implement guidance.

5.3.1.2. Measuring the Implement Lateral Position with Respect to the Vehicle.

Based on the three-point hitch geometric model and the sensory system setup, it is possible to relate the potentiometer measurements with the actual lateral displacement of the implement. Figure 5.8 shows a schematic model of the three-point hitch to implement connection, where Δd is the difference in the

[1] Unimesure Inc., model JX-EP-20-N14-110-25C; http://www.unimeasure.com/

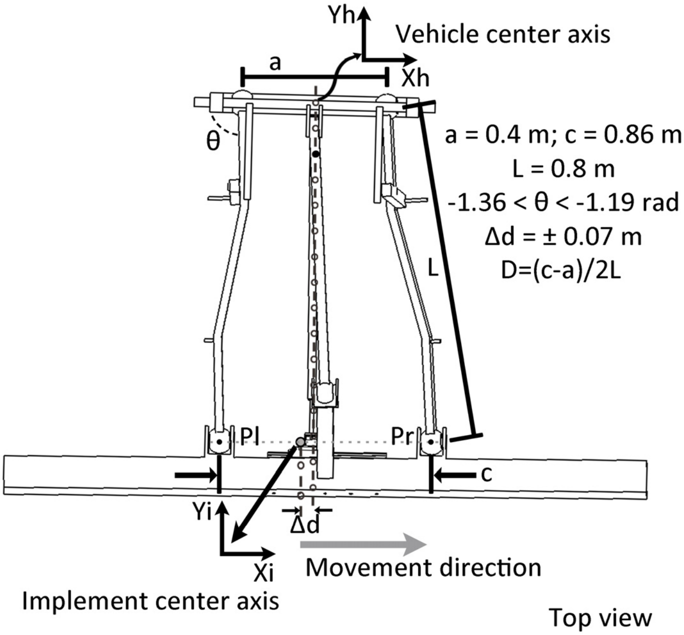


Figure 5.8. Schematic model of the three-point hitch to implement connection.

potentiometer measurement and ΔX is the real implement displacement with respect to the center of the vehicle. Based on the geometric model of the three-point hitch, Equation (5.1) and Equation (5.2) represent the positions of the points *Pl* and *Pr* with respect to the central reference axis h (See Figure 5.8). Equation (5.3) represents the position of the point *Pr* as a function of θ, which represents the excursion angle of the three-point hitch left arm. Equation (5.4) represents the implement center axis *i*, as a function of *Pr* and *Pl*. Given the geometric model of the link between the three-point hitch and the implement and knowing the dimensions of the arms and the range of θ (See Figure 5.8), it can be calculated that, in the case of implement maximum excursion, the real displacement ΔX, described in Equation (5.5) is 0.17% greater than the measured displacement Δd, described in Equation (5.7), which is negligible.

$$(X_{Pl} - (Xh - a/2))^2 + (Y_{Pl} - Yh)^2 = L^2 \tag{5.1}$$

$$(X_{Pr} - (Xh + a/2))^2 + (Y_{Pr} - Yh)^2 = L^2 \tag{5.2}$$

$$(X_{Pl}, Y_{Pl}) = \left((Xh - a/2) - L \cdot \cos\theta, Y_{\mathrm{h}} - L \cdot \sin\theta\right) \tag{5.3}$$

$$(Xi, Yi) = (Pl + Pr)/2 \tag{5.4}$$

$$\Delta \mathrm{X} = Xh - Xi \tag{5.5}$$

$$\Delta Y = (Yh - \left(\sqrt{1 - D^2}\right) \cdot L - Yi \tag{5.6}$$

$$\Delta \mathrm{d} = \sqrt{\Delta \mathrm{X}^2 + \Delta \mathrm{Y}^2} \tag{5.7}$$

5.3.2. Characteristics of the Actuation System

Following the properties described for the perception system in Section 2, the actuation system exhibits the following characteristics:

a) Flexibility/modularity

The actuation system consists of a main frame and simple actuators that apply a given process to the crop. In this sense, the main frame and the related positioning systems can be used for a large number of crops, and the specific actuators (burners, nozzles, etc.) can be easily changed for different crops. As agricultural vehicles normally provide electric and hydraulic power, there are many different types of actuators that can be used in these devices. This makes the actuation system have little dependence on the type of crop to be treated.

b) Scalability

The number of electrical, hydraulic or pneumatic actuators (relays, prismatic cylinders, etc.) that can be connected depends on the number of I/O channels provided by the Main Controller. The specific controller used in this work (See Section 5.4) allows the designers to use a large number of I/O channels that can be even cascade-connected, which makes the number of I/O ports nearly unlimited. Scalability is thus a minor problem.

c) Robustness

As the actuation systems consist of a main frame made of steel and a number of commercial actuators that are rugged enough for use in industrial and natural environments, the system exhibits high robustness.

d) Real-time/Performance

The lateral positioning of the main frame requires a simple PID controller that does not require high computing power, and signals are activated normally through a CAN bus that has few delays. However, hydraulic valves can have a slow response, jeopardizing the control performance. Thus, real-time performance in actuation systems is critical and must be carefully designed.

5.3.3. Process: Integration of Information

The actuation system consists of two main tasks: a) controlling the activation/deactivation of the burners and b) controlling the lateral positioning of the main frame with respect to the vehicle. The first piece of information comes directly from the vision system (camera-based sensor and processing), which informs the exact points where the treatment must be applied based on a weed coverage matrix. The second piece of information comes from the location system (GPS), which indicates the position in which the implement must be a few seconds later, depending on the vehicle's speed, position with respect to the crop lines, and the variations of the heading.

5.4. Decision Making and Control

The perception system is integrated and communicates with the High Level Decision-Making System (HLDMS) that constitute both the hardware part (Main Controller) and the software part (drivers, functions, algorithms, etc.) of the element of integration and control of a fully autonomous agricultural system. Moreover, a part of the actuation system, which is in charge of the implement lateral control, is also integrated in the HLDMS. This system is primarily responsible for synchronizing the information coming from the different sensors to associate the same reference system for each piece of information and selecting the best behavior depending on the situation, the perceived environment and the general mission to be performed. Thus, the relationship is created between what is perceived and where and when the actuation is needed.

Others important tasks of the HLDMS are: a) the interpretation of the information; b) the evaluation of its reliability; c) the creation of an action plan to be executed by the actuation system; d) the communication with external users and other devices; and e) the supervision of the development of the general mission.

5.4.1. Description of the High-Level Decision-Making System

The HLDMS is in charge of collecting the information provided by the sensors about the environment, producing the actuation plan, and monitoring the execution of the various tasks that make up the general mission. The information must be synchronized, processed, interpreted, and arranged for decision making with the purpose of actuating over agricultural fields. This system is also in charge of sending messages to the sensors and actuators to demand specific behaviors on the corresponding devices. The selection of the Main Controller and its architecture was introduced in Chapter 4.

5.4.1.1. Funcions and routines that constitute the HLDMS

Figure 5.9 presents a general diagram of the internal structure (software architecture) of the HLDMS. As presented in Chapter 4, this system consists of three different software levels: 1) the basic drivers (yellow boxes), for communication with the external subsystems; 2) basic routines (black and purple boxes), for processing and interpretation sensors and communication data; and 3) the decision-making module (red box), which is in charge of integrating, planning and generating the desired behaviors for meeting the goals defined by the user in the mission. A detailed description of each subsystem, routine and function are described as follows:

a) General functions: these are the main functions for vehicle guidance, implement control, and user control and supervision in a general agricultural application.

a.1) Localization routine: this routine acquires the global position of the vehicle (through the GPS receiver) and transforms it into a relative position with respect to a point in the field configured by the user.

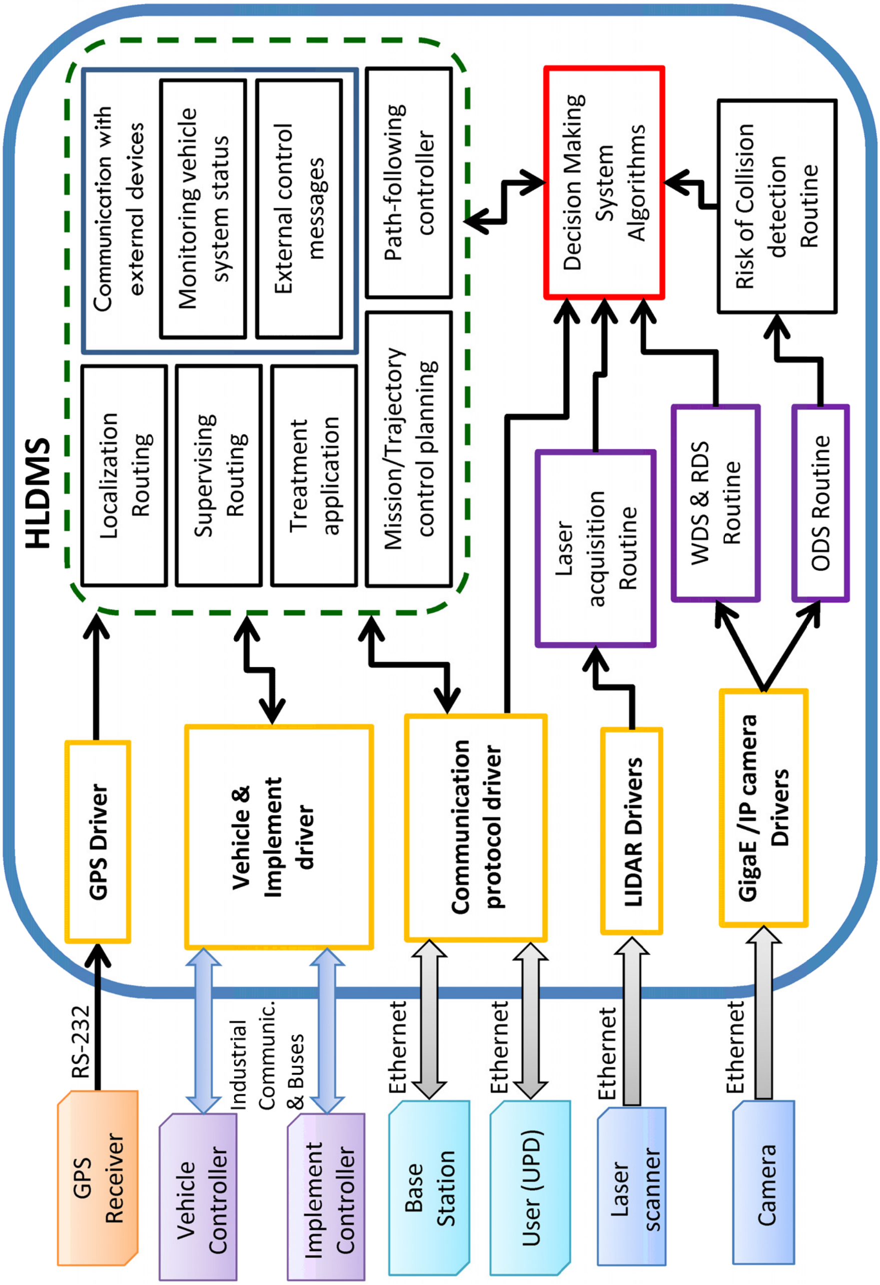


Figure 5.9. General scheme of the functions, routines, and subsystems that constitute the High Level Decision-Making System.

a.2) Monitoring vehicle system status: this routine establishes a communication link between the vehicle and the user (as Base Station or portable device) and generates the essential information required by the user (relative position on the vehicle, vehicle's status, implement's status, alarms and notifications).

a.3) External control messages: are high level messages that instantly generate new behavior or change in the current system status. Some examples of these messages are: establishing a new general mission, system configuration, moving, pause/resume, stop, change state of some elements of the implement (open/close, on/off, etc.), among others.

a.4) Supervising routine: this routine is in charge of collecting all type of information from the diverse subsystems on the vehicle and analyze is reliability and if it is working properly. For example: a) if the sensors, computers, subsystems, and sub-routines are working properly (e.g. memory management, temperature monitoring, time critical compliance); b) if the information acquired by the perception system is valid (e.g. the received images are not updated, exposure time wrong); c) if the vehicle is following the predefined path correctly and within the permitted errors. Another task of this supervising routine is the generation of alarms to inform the user about the on-board problems or the accomplishment of a specific task (e.g. informing if an obstacle was detected by the ODS system or by the Laser; informing about a failure in one subsystem or sensor; reporting on the completion of the general mission or a specific task).

a.5) Mission/Trajectory control planning: this function in is charge of generating the corresponding straight lines and curves to link the waypoints that constitute the general mission sent by the user. Each waypoint, consisting of a relative XY position, heading, and desired speed, is connected to the next waypoint on the list using Dubins Curves (Dubins, 1957). Each segment of the generated path is sent to the path following controller consecutively in order to follow the whole path continuously and smoothly.

a.6) Path follower controller: this function is in charge of generating the corresponding reference values of speed and wheel rotation angle to follow, via GPS localization, each segment of the generated path. This controller is based on a Fuzzy Logic algorithm developed by Emmi et al. (2012).

a.7) Treatment application: this routine takes as input the desired implement status in each instant of time and synchronized with the implement to execute the planned treatment. This implement status information can be generated directly by

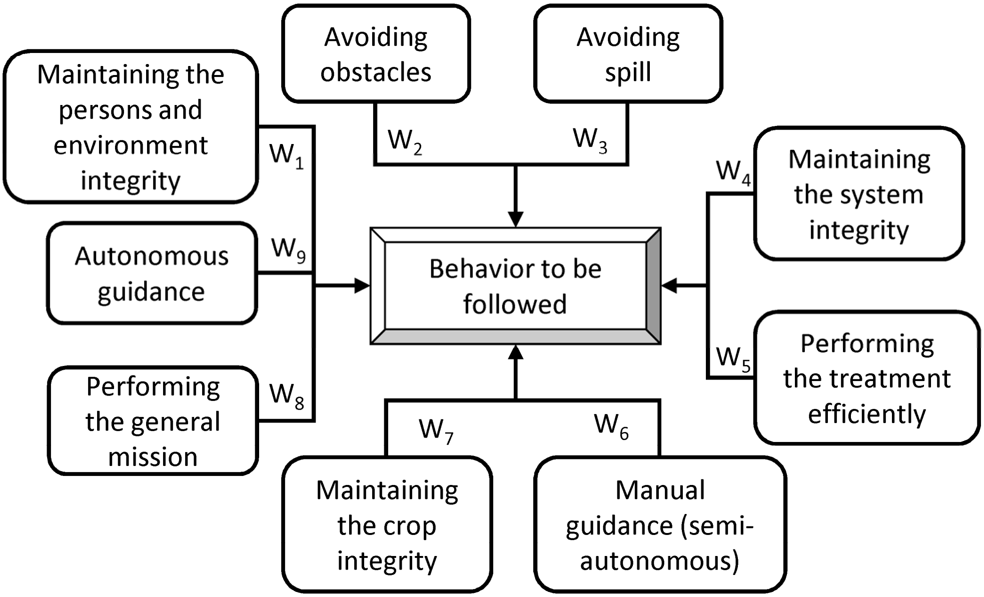


Figure 5.10. General diagram of possible behaviors that a fully autonomous agricultural system can perform.

the user, in applications where the field information and the treatment is known in advance, or by the on-board perception system, prior analyzed and processed by the decision-making algorithms.

a.8) High-Level Decision-Making System Algorithms: these algorithms take as inputs the information interpreted and processed by other routines, and based on that results modify or maintain the behavior of the system. Figure 5.10 presents a general diagram indicating some possible behaviors that the system must follow. The selection of the correct behavior is based on its weigh with respect to the others and depends of the current situation, location and treatment to be performed by the vehicle, among others. Given that the situation in which this controller was tested is a close controlled environment, the boundaries of the field are well known (fixed obstacles known), the possible obstacles in the vehicle way can be moved and normally cannot be there, the HLDMS requires algorithms that are not so complicated. Basically, the decision-making system resolves if the vehicle has to 1) continue performing the mission, pausing (the vehicle and the treatment are put on standby, waiting for the solution of the problem and the resume by the user) or stopping the vehicle (the mission is aborted, the vehicle is stopped and the implement is closed), when some failures or possible risks to the environment or to the vehicle are present.

b) Specific functions: these are functions for vehicle guidance and implement control for a specific application or treatment that requires extra sensorial or actuation systems to performing the mission properly.

b.1) Weed and Row Detection system routine (WDS & RDS): this routine is enabled depending on the treatment that the user wants to perform and is specific for some applications like the ones concerning wide row crops. This routine uses the on-board camera to identify the crop rows and the weed infestation. Section 5.2 describes with high detail the algorithms and criteria used for the realization of these two tasks.

c) Safety functions: these are functions to maintaining the safety requirements of the system by detecting obstacles in the path of the vehicle in real-time.

c.1) Laser acquisition routine: this routine is in charge of acquiring and interpreting the information provided by the Laser, and associates each information packages with a GPS position. If an obstacle is detected in a safety area, the vehicle is paused by the safety controller of the tractor.

c.2) Obstacle Detection System (ODS) routine: this routine is a safety element in charge of detecting and discriminating obstacles through machine vision. The algorithm running on this routine was developed by (Hödlmoser et al., 2011), integrated in the Main Controller. Based on the computational charge, this routine works at 3 fps and has as output a list of obstacles discriminating if is a person or other object. This list is sent to the *Risk of collision detection routine* which proposes correct behavior to confront the presented situation.

c.3) Risk of collision detection routine: it interprets the information from the ODS routine by deciding if the vehicle or some elements in the environment are in risk of collision and established the optimal behavior of the vehicle for each situation.

5.4.1.2. Making Decisions Based on the Reliability of the Information of the Perception System.

Although the commercial devices in the perception system are very trustworthy, some disturbances may occur from the interaction with the environment that can affect the quality of the acquired information. Some of these disturbances include a decrease in the GPS precision or the loss of messages, as well as disturbances in the images due to reflections or lighting changes. Such disturbances can be detected in real time, and based on the degree of influence of the disturbance an estimation of the reliability of such information can be made.

The failure, loss or alteration of information directly affects the precision with which the treatment is performed at that instant in time, given that in this type of application, the vehicle is in motion and the treatment is being fulfilled based on that movement. For example, in the case of low reliability in the generation of a weed cover map in a small section of the mission, it is better to apply the treatment with the worst-case scenario rather than returning to that specific area.

5.4.2. Characteristics of the High-Level Decision-Making System

Based on the above considerations, this subsection proposes a design that meets the above requirements under LabVIEW (Travis and Kring, 2006), where the four properties identified as appropriate for architectural design in agricultural robots can be summarized as follows:

a) Flexibility/modularity

The HLDMS receives/sends data from/to the perception and actuation systems when required. They are directly connected to the corresponding devices, and these data are mapped as variables in LabVIEW. All processing and control modules are written as functions (subVIs[1] in LabVIEW) that are linked together. The image processing module is a DLL developed in C++ and is also written as a subVI. This means that all modules can be easily replaced, added or removed according to the specific needs of each agricultural application.

b) Scalability

The architectural design achieves a high level of scalability because the system can grow simply by adding new functionalities embedded as new modules and connected with internal links.

[1] SubVIs are thus analogous to subroutines for LabView programs and allow the LabView program to be organized into a hierarchy

c) Robustness

cRIO supports a high range of working temperatures (0 ºC to +55 ºC), with ingress protection IP20 and operational humidity up to 90%. This computer supports operational sinusoidal vibrations up to 500 Hz at 5 G. The system has been tested in real, harsh agricultural conditions and can accomplish real tasks with extraordinary robustness.

LabVIEW has also been tested successfully in different robotics systems including autonomous agricultural robots (Bakker et al., 2010b). Part of this feature is achieved by suppressing the external links of communication between the different modules in charge of the different devices. Only local protocols are required to arrange ordered data coming from the different systems.

d) Real-time/Performance

LabVIEW is specifically designed for running under a real-time operating system. It allows remote communications via Wi-Fi, where limits are established by the Wi-Fi network and not by LabVIEW. This program is suitable for communications with a base station.

5.4.3. Process: Integration of Information

The HLDMS is in charge of three main tasks as described previously: a) perception and actuation synchronization; b) trajectory planning; and c) weed coverage map interpretation.

The HLDMS knows the general mission to be performed, and based on that assignment the plan that meets the most optimal execution (shortest distance) is fulfilled. This planning consists of sub-paths where the vehicle follows straight or curved lines, linking a starting and a final point. The RTK-GPS is the main sensory system to close the control loop for path following and is corrected when necessary by the camera-based system. The HLDSM sends the planned sub-path to the actuation system, which is in charge of the path following, and can be a sub-system inside the HLDSM or an external device.

Along each sub-path, the HLDMS commands the perception system to acquire images in coordination with the navigation speed. Each order is triggered every two meters in front of the tractor along each sub-path. This measurement is fixed by the length of the ROI, and the exact positions are provided by the GPS. Full area coverage should be guaranteed to avoid gaps and uncovered areas.

5.5. Results

Various experiments have been conducted to assess the performance of the proposed architecture. The experiments have been carried out in the experimental fields at the CSIC-CAR facilities in Arganda del Rey, Madrid, Spain, on different dates, during May/June/July and October 2013, and additional calibration tests were carried out in December 2013. We have tested our whole system in two different maize fields with sizes of 15 m by 60 m and 18 m by 48 m respectively, i.e., with sufficient lengths to travel along different paths.

During the first phase, both the perception and actuation systems were verified separately, and during the second phase, the systems were checked together under the supervision of the High-Level Decision-Making System.

5.5.1. Perception System Assessment Tests

As mentioned previously, the operation speed defined for this application was 0.83 m/s (3 km/h) and the ROI was defined to be 3 m wide and 2 m long. These parameters mean that every 2.4 s, the perception system must be able to provide all required data processed and ordered, i.e., with correct synchronization between them. We have analyzed more than 5000 images with the corresponding GPS and IMU data. A first set of tests was carried out to verify that the data acquisition was synchronized and on time. A second set of tests was intended to verify the accuracy of guidance and weed detection.

5.5.1.1. Execution Time Tests: Data Acquisition and Processing

Table 5.1 displays the average time spent in the process of image acquisition and interpretation, beginning with image capture and transmission to the availability of data by the decision-making algorithms. The camera sensor time is split into two parts. The first part is the image acquisition time, which includes the exposure time required to excite the sensor and the time for image transmission to the Main Controller until it is available for the HLDMS. The second part is the image processing averaged time, where the computational time differs depending on the density of greenness (crop/weeds) existing in each image.

Table 5.1. Averaged times required by the perception system until data are available for control and actuation.

	Vision System			GPS	IMU	Synchronization (next treatment segment)
	Image acquisition	**Image processing**	**Perception (Sub-total)**	**Acquisition**	**Acquisition**	
Average Time (ms)	**50**	**250-300**	**300-350**	**1**	**1**	**2.4 s**
Refresh rate (Hz)	**10**	**3.3**	**2**	**10**	**50**	**-**

The data presented in Table 5.1, unlike the data presented in Table 4.1, are results obtained in real-time while the autonomous vehicle performed a real site-specific weed control application. Besides this, the frame rate in these tests was increased up to 10 images per seconds, allowing more images to be available for a better representation of the environment.

From the results in Table 5.1, we can see that the time spent for the perception system (subtotal column) is below the required 2.4 s. Moreover, we have time enough to increase the tractor's speed when required and depending on the specific agricultural task. Minimum frequencies are defined for refreshing data, although normally, the information of the processed image is available when the vehicle travels the operation area segment.

5.5.1.2. Synchronization Tests: Geo-positioning an Image

After confirmation of the ability by the Main Controller to complete the treatment throughout the work area within the time requirements without losing information, the next element to be evaluated is the accuracy of the information obtained by the perception system related to positions on the field, based on the vision system setup in Figure 5.4. Given the situation presented in Section 5.2.4, the synchronization of one acquired image with respect to a GPS position is not a trivial task and introduces an error associated with the non-deterministic transmission process. The simplest solution is to store the last GPS position available just before sending the command to the camera to acquire an image. This creates an uncertainty regarding whether the acquired image corresponds to the stored GPS position or to a subsequent position, taking into account the age of the stored GPS data, among other factors. A set of tests was carried out following this synchronization approach, where we can draw two interpretations: one related to the error associated with geo-positioning the weed coverage matrix (longitudinal error), and another interpretation of the error related to the deviation between the detected crop lines and the line-of-sight supplied by the perception system (lateral error).

a) Computing the longitudinal error: weed coverage matrix geo-positioning.

Given the vision system setup described in Figure 5.4, the image acquired was calibrated to associate a point (pixel) in the image as a displacement (in meters) with respect to the reference frame *OXYZ* presented in Section 5.2.1. This displacement is given by:

$$l(y) = 4.539 \times 10^{-6} \cdot y^2 - 0.0136 \cdot y + 6.822 \tag{5.8}$$

where y is the value of the pixel in the longitudinal axis representing the point or mark in the ground whose distance from the camera wants to be known. Equation (5.8) is only valid for pixels with the y coordinate aligned at the center of the image and within ± 1 m from the start of the ROI presented in Figure 5.4.

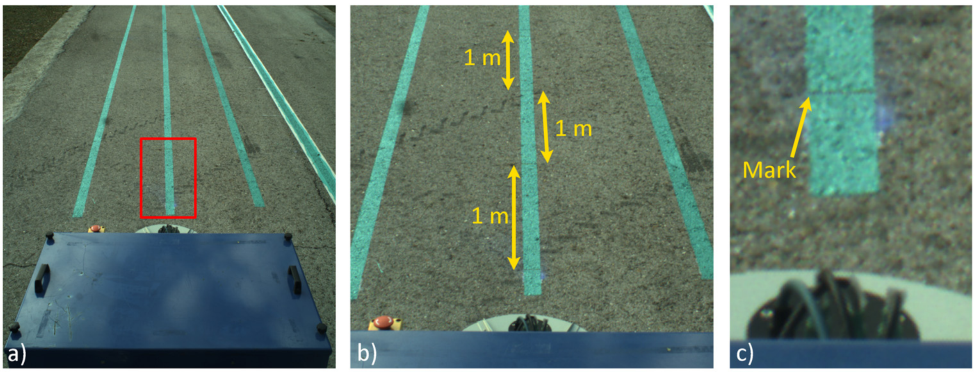


Figure 5.11. Example of the test conducted for computing the longitudinal error of the vision system. Image acquired and diverse zooms. (a) Original image. (b) 200% zoom; 1 m apart between marks. (c) 800% zoom; mark location: pixel(y) = 1103.

This calibration has an associated error of ±0.02 m, due to human inaccuracy when selecting the correct pixel and vehicle vibrations transmitted to the frame onto which the camera is fixed.

Using the vision system characterization, a set of tests was conducted where a series of marks were drawn in a plane soil (See Figure 5.11) 1 m apart from each other and the vehicle followed a straight line over the marks (approximately 12 m at 0.83 m/s) and acquired images at a rate of 10 fps. Subsequently, the images where the marks were within the valid area were selected and compared with the real location of each mark. The mean square error between the theoretical position of each mark and the estimated position was 0.08 m. This result coincides with the distance between two consecutive GPS positions (at working speed). Taking into account that no synchronization element was implemented except for the matching of the frequency for the GPS and image acquisition, this experimental result validates the assumption that the acquired image must be within ± 0.08 m of its associated GPS position in the longitudinal axis.

b) Computing the lateral error: crop row detection

Regarding the error associated with the measure of the lateral displacement of the line-of-sight related to the crop lines detected by the perception system, this error is directly related to changes in the heading of the vehicle in the instant in time when the image is acquired. This heading variation is due to the process of image geo-positioning, which entails a translation of the GPS position acquired in that instant in time (corresponding to the position of the CCD sensor, See Figure 5.4) to the beginning of the ROI. To estimate the associated error, a set of tests was conducted where the vehicle crossed the maize field several times, and using the information generated by the perception system, small adjustments for row following were executed (which generated changes in the heading). Figure 5.12 illustrates one of the recording changes in the heading of the vehicle, and Table 5.2 shows the results of all sets. Equation (5.9) defines the variations in the lateral deviation of the line-of-site based on the variations of the heading.

$$\Delta d = \sin(\Delta\varphi) \cdot L \tag{5.9}$$

where L is the distance between the beginning of the ROI and the main coordinate system of the vehicle (which corresponds to the rear axle) and has an associated error of ±0.08 m from the geo-positioning procedure.

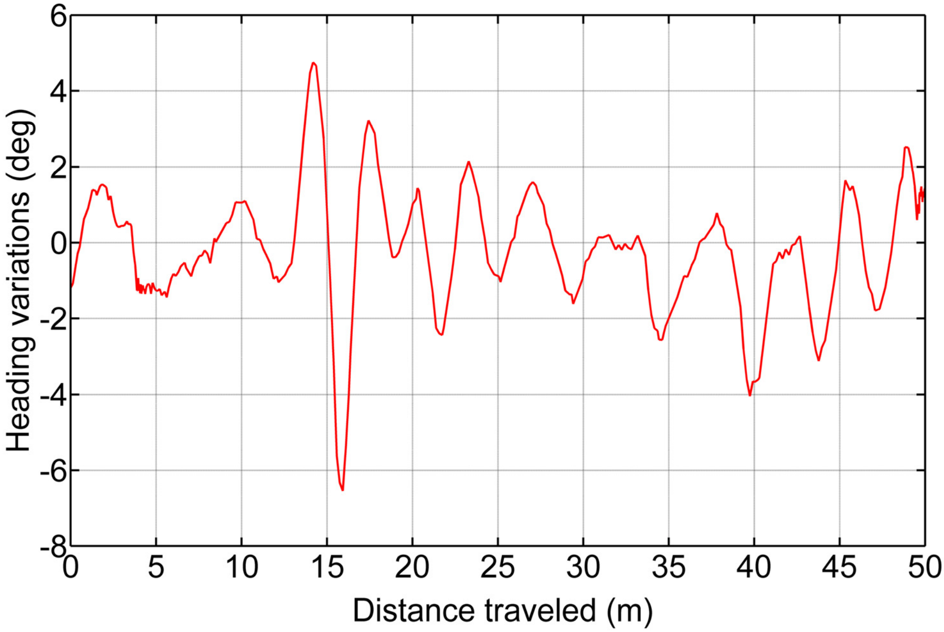


Figure 5.12. Example of heading variations with respect to the theoretical value when the vehicle is crossing the maize field.

Table 5.2. Standard deviations of the variations of the heading and the error associated with the calculation of the lateral displacement of the line-of-sight related to the crop lines detected by the perception system.

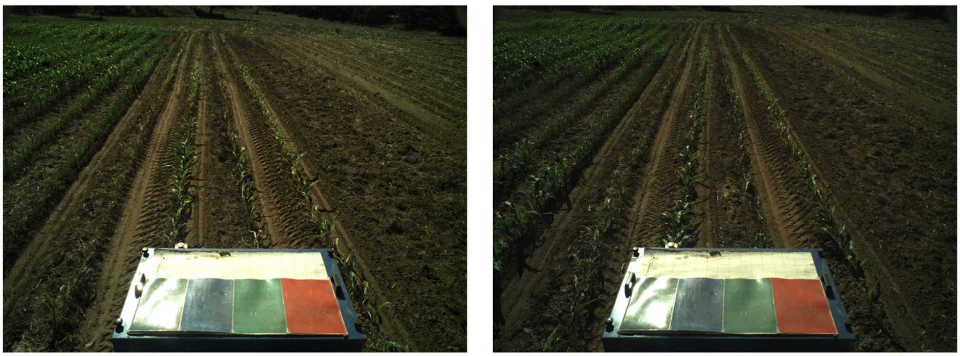
	Standard deviation of the variation of the heading $\Delta\varphi$ (deg)	**Error associated with the measurement of the lateral deviation Δd (m)**
Set 1	**0.36**	**0.03**
Set 2	**0.26**	**0.03**
Set 3	**0.24**	**0.02**
Set 4	**0.32**	**0.03**
Set 5	**0,18**	**0.012**
Total	**0.27**	**0.03**

5.5.1.3. Image Processing Tests

a) Correcting the vehicle trajectory with crop row detection

Crop row detection is a crucial task for guidance and weed detection. The first test consists of the analysis of the correct line detection and the tractor's trajectory correction when required. We have randomly selected 400 images acquired during the May/June and October 2013 tests at the CSIC-CAR facilities in Arganda del Rey (Madrid, Spain). The images were acquired over several days under different illumination conditions, i.e., cloudy, sunny days, and days with high light variability. Each processed image is associated with the GPS and IMU data as well as the corrected value for guidance. Given the crop lines, we chose the two central crop lines and determined the correction by computing the deviation of the central line with respect to an imaginary vertical line that divides the image into two equal halves. This deviation was computed in pixels and transformed to a distance based on image calibration (Romeo et al., 2013).

Figure 5.13 displays a sequence of two images acquired during the execution of a straight trajectory following a planned path. Figure 5.14 displays the corresponding processed images with the crop lines detected in the ROI and the weeds identified; we can see the weeds detected around the crop lines. As previously mentioned, the crop lines also serve as local corrections when path planning deviations occur. The tractor in Figure 5.14(a) undergoes a slight deviation from the planned trajectory. Indeed, we can see that the upper right corner in the box, belonging to the tractor, is very close to the rightmost crop row and that this box is misaligned with respect to



a) b)

Figure 5.13. Consecutive original images acquired by the perception system. (a) Deviations of the tractor with respect to the crop lines. (b) Correction of this deviation.

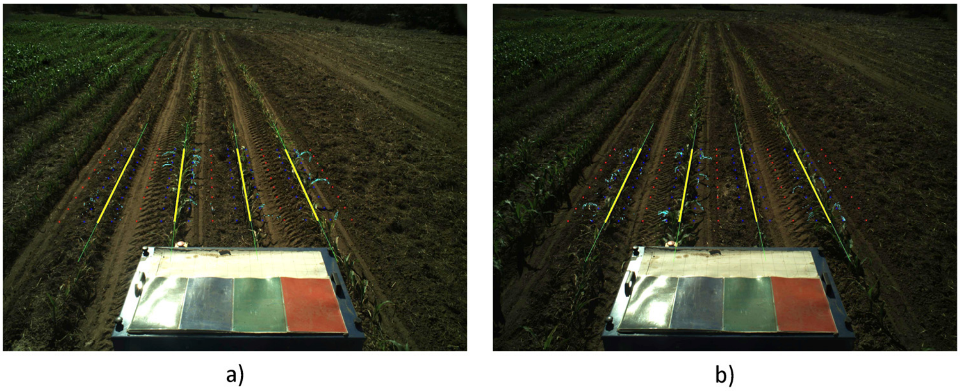


Figure 5.14. Processed images with the detected crop lines corresponding to images in Figures 12.a and 12.b, respectively.

the four crop lines detected in the image displayed in Figure 5.14(a). This misalignment is corrected and can be observed in the subsequent image (See Figure 5.14(b)), where the box is better centered relative to the crop lines. This correction is carried out without delays as expected under the proposed architecture. The situation displayed in the above images was normal in our experiments because the tractor navigates on rough agricultural fields with some irregularities.

From the set of the 400 selected images, we have verified the corrections ordered by the vision system, assuming that corrections below 0.03 m are ignored and that the path following continues with the GPS. After each correction, we verified that the tractor in the next image in the sequence is conveniently positioned. We have verified that on average, a correction has been demanded for 30% of the images (120 images). From these, we have verified that the tractor was correctly positioned on 89% of the subsequent images. For the remaining images, the correction was erroneously demanded. In this case, the path following based on GPS assumed full responsibility of the guidance.

In Figure 5.15, the comparison between the use of the information provided by the crop row detection system and using only GPS for crossing the maize field is illustrated, where it is noteworthy that the crop row detection system slightly improves the row following, taking into account that the theoretical path to be followed using only the GPS system corresponds to the center of the row by which the two results are compared. It is worth noting that the crop rows at the end of the experimental field were slightly damaged (the last 10 m), due to the large number of

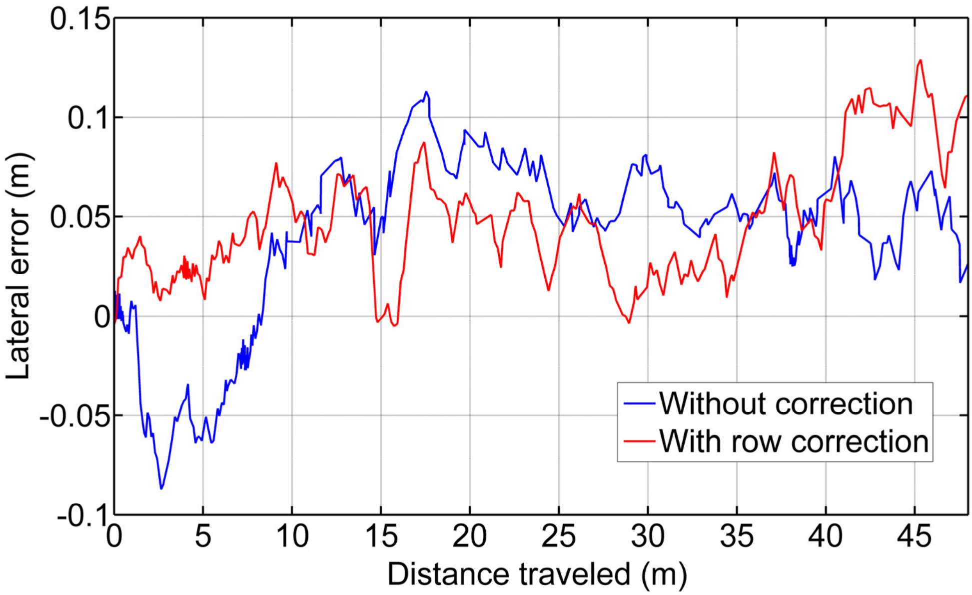


Figure 5.15. Comparison of the vehicle guidance in a maize field, represented as the lateral error of the rear axle with respect to the theoretical center of the rows

tests performed, and in this area, the vision system for crop row detection produced a large number of errors.

b) Weed detection

For each image, we also computed and stored a density matrix of weeds associated with the image. This matrix contains low, medium, and high density values. It is assumed the camera is calibrated and arranged conveniently considering intrinsic and extrinsic parameters (Romeo et al., 2013). Figure 5.16 illustrates two consecutive images along a sub-path. They contain three types of lines defining the cells required for computing the density matrix as follows:

1. Once the crop lines are identified, they are confined to the ROI in the image (yellow lines), which covers fixed positions in the image.
2. To the left and right of each crop line, parallel lines are drawn (red). They divide the inter-crop space into two parts.

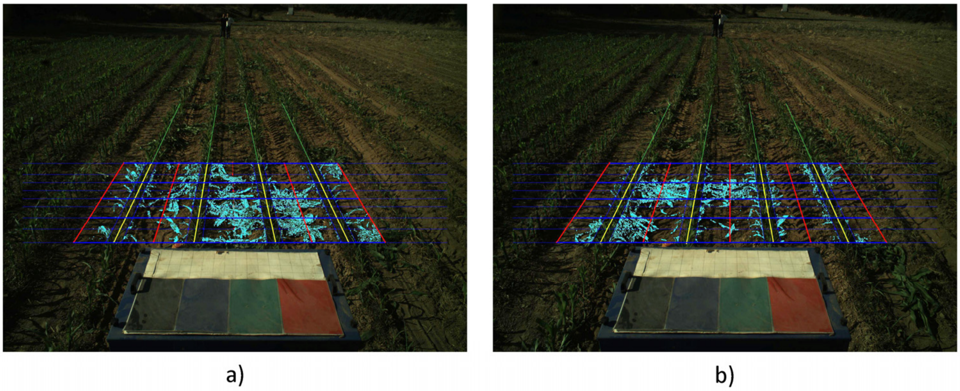


Figure 5.16. Consecutive images along a sub-path with the detected crop lines (yellow); parallel lines to the left and right crop lines (red); horizontal lines covering 0.25 m in the field.

3. Horizontal lines (in blue) are spaced conveniently in pixels so that each line corresponds to a distance of 0.25 m from the base line of the spatial ROI in the scene.
4. The above lines define 8 × 8 trapezoidal cells, each trapezoid with its corresponding area A_{ij} in pixels. For each cell, we compute the number of pixels identified as green pixels, G_{ij}, (drawn as cyan pixels in the image). We exclude the pixels close to the crop lines with a margin of tolerance, which represents 10% of the width of the cell along horizontal displacements. This is because this margin contains mainly crop plants but not weeds. The weed coverage for each cell is finally computed as $d_{ij} = G_{ij}/A_{ij}$. The different d_{ij} values compose the elements of the density matrix.

From a set of 200 images, we have classified the coverage with three levels (Low, $d_{ij} \leq 33\%$, Medium, $33\% < d_{ij} \leq 66\%$, and High, $d_{ij} > 66\%$). These percentages are checked against the criterion of an expert, who determines the correct classification. We have obtained a 91% success rate.

5.5.2. Sensing/Actuation System Test

To measure and validate the accuracy of the sensory system, several tests were performed with the following results:

5.5.2.1. Computing the Error Associated with the Sensory System in Measuring the Lateral Displacement of the Implement with Respect to the Vehicle

a) Static Tests: accuracy of the acquisition module

This trial consisted of acquiring static position measurements from the potentiometer when the implement was placed and anchored at three different displacements with respect to the vehicle (Set 1, Set 2 and Set 3) (See Figure 5.17). This test confirms the proper operation of both the potentiometer and carriage displacement systems and states that the potentiometer measurements have a mean absolute error of ± 0.0003 m, given by the standard deviation of the diverse sets (See Table 5.3).

Table 5.3. Standard deviation and variance of the data presented in Figure 5.17.

	Standard deviation (m)	**Variance (m^2)**
Set 1	**0.000256897**	**6.59961E-08**
Set 2	**0.000224263**	**5.02939E-08**
Set 3	**0.00025533**	**6.51932E-08**

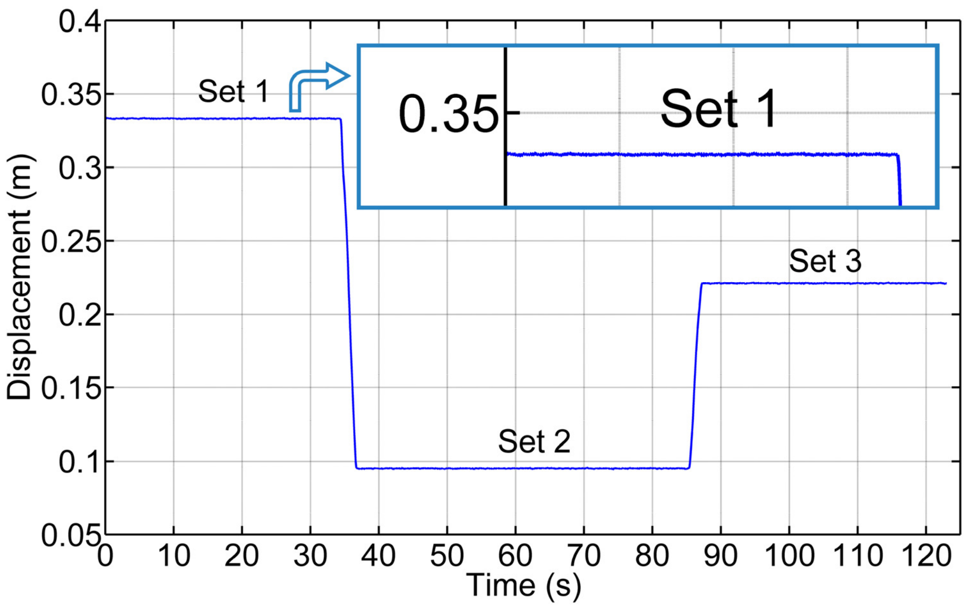


Figure 5.17. Measuring the position of the sensor in static tests.

b) Deflection test: Measuring the error added by the rod bending and the junctions

Because the sensory system has a 1-m-long arm, the deflection of the arm generates a measurement error. Additionally, the link between the arm and the two joints in both ends has a certain degree of backlash. To measure the error added by this deflection/backlash, the implement was fixed relative to the vehicle and an external force was added to the carriage, generating deflection of the materials and measuring the maximum ranges. Figure 5.18 shows diverse sets of forces applied to the carriage: Set 1 and Set 3 forces the system to the right, and Set 2 and Set 4 force it to the left. This test does not seek to develop a model of the deflection of the materials that make up the sensory system but instead aims to determine, in the worst case, how much such deflections/backlash affects the final lateral displacement measurement of the implement with respect to the vehicle. Moreover, maintaining a certain degree of deflection in the sensory system reduces the number of system blocks and breaks. The total error due to arm deflection and backlash of the joints is ±0.004 m.

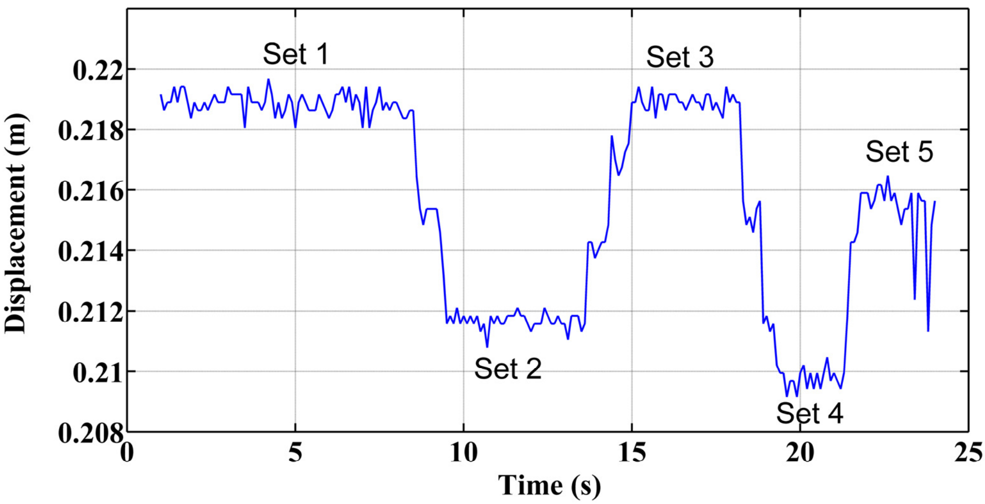


Figure 5.18. Measuring the position of the sensor where external forces are flexing the sensorial system.

Table 5.4. Mean displacement values of the sensory system due to material flexing.

	Mean Value (m)
Set 1	**0.2189±0.0003**
Set 2	**0.2117±0.0003**
Set 3	**0.2189±0.0003**
Set 4	**0.2087±0.0003**

c) Dynamic tests: Measuring the error of the entire sensory system while the vehicle is in motion

A final test was conducted to measure the variations in displacement while the implement is modifying its lateral position with respect to the vehicle and the vehicle is following a straight line at 0.83 m/s. This test defines how much the sensor dynamics affect the control of the lateral displacement. To validate the entire system, a Sick Laser LMS100 pointing to a 0.03 m wide bar located at the center of the implement was installed at the bottom of the vehicle. The laser detects the bar as a peak in the readings, and by measuring the movement of that peak in the transverse axis it was possible to determine with very high accuracy the position of

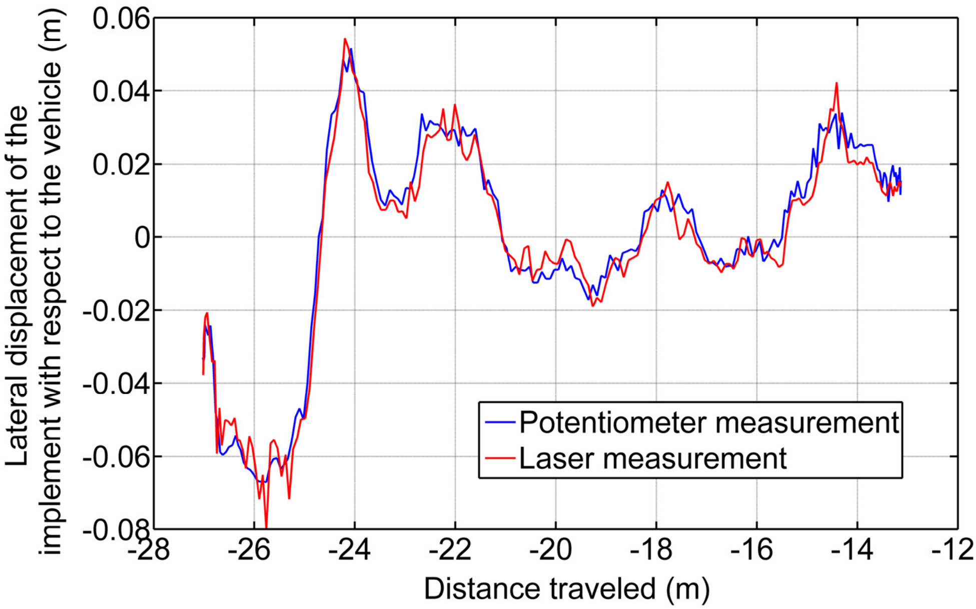


Figure 5.19. Comparison of the readings of the Laser compared with the output of the potentiometer.

the implement with respect to the center of the vehicle. Both the laser information and the potentiometer information were related and synchronized with the GPS. Given that the laser was configured to have an opening angle between beams of 0.25 degrees and the bar was 1.2 m apart from the Laser, this validation system had a resolution of 0.0052 m. Figure 5.19 illustrate the results where the laser measurements are compared with the potentiometer measurements. The mean absolute error calculated was ±0.004 m.

5.5.2.2. Results of the Control for the Adjustment of the Implement Lateral Displacement with Respect to the Vehicle

For lateral control of the implement, two PID controllers in cascade configuration were implemented (See Figure 5.20). The first controller (*Cwg(s)*) is responsible for adjusting the hydraulic piston that defines the position of the steering wheels of the implement. The second controller (*Cld(s)*), given a desired setpoint of the lateral displacement of the implement (*ld(s)*), generates the desired steering signal. Figure 5.21 presents the response of both controllers, where the vehicle was moving in a straight line at 0.28 m/s. The response time of the wheel guidance controller was set based on the system that it replaced (an operator with a steering wheel), and the response time of the implement lateral controller depended on the speed of the vehicle. Figure 5.22 illustrates an example of the implement lateral-position control with three diverse setpoints. Although it is observed that the implement is not maintaining the desired position for each setpoint due to disturbances from the soil (*d(s)*), the results obtained are encouraging.

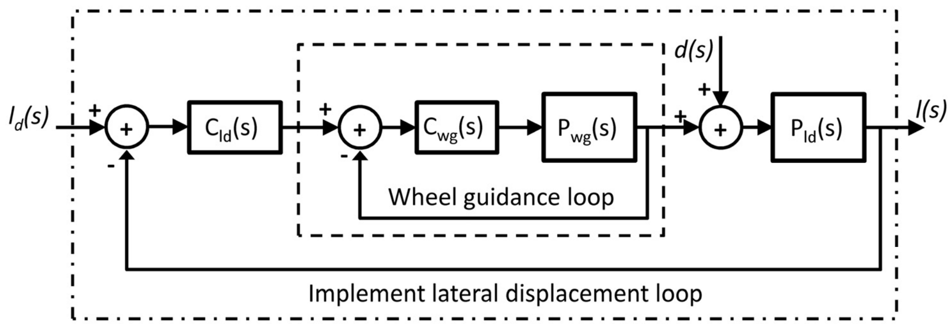
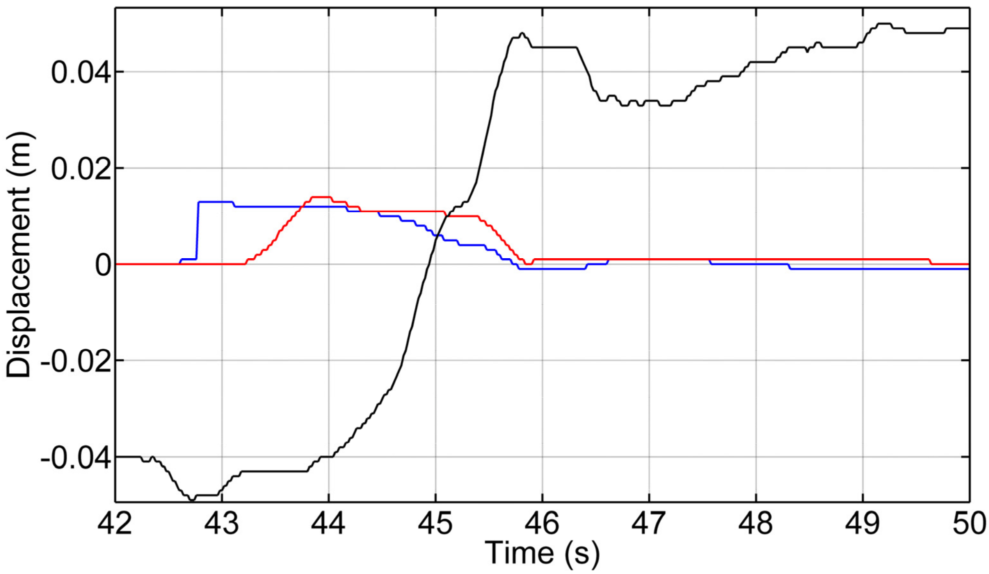


Figure 5.20. Schematic diagram of the PID controller in cascade configuration for controlling the lateral displacement of the implement with respect to the vehicle.



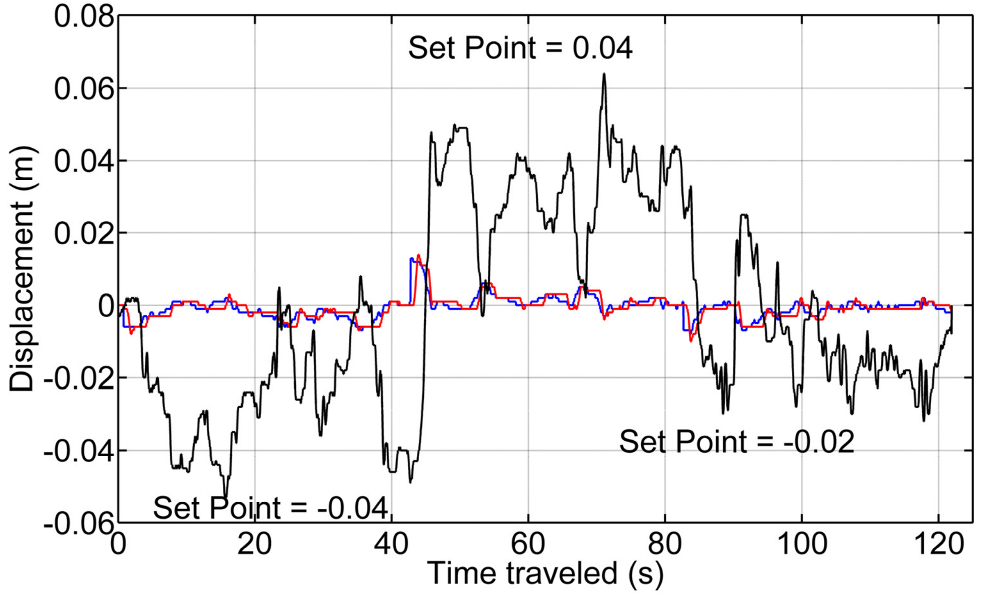


Figure 5.22. Experimental results of the implement lateral displacement control with three different setpoints.

We have been able to keep the implement around the desired position with a mean absolute error of ±0.01 m for a complex and heavy system with a very important dynamic response.

5.5.2.3. Calculation of Delays in the Thermal Treatment

As a final test of each individual elements presented in this chapter, the calculation of delays associated with the treatment for weed control is presented. A set of tests was performed to detect in which GPS position the burners turn on and off, using an IP camera mounted on the back of the implement pointed to a set of burners. The method to associate an image with a GPS position is the same synchronization approach presented in Section 5.5.1, which has an error of ± 0.1 s. For conducting such tests, a straight path was defined, and within that path, a set of points where the burners were turned on and off consecutively was selected (See Table 5.5).

Table 5.5. Relative UTM positions where the ignition and extinction commands were sent, the associated relative UTM positions where the action was detected, and the produced delays.

		Desired Position (Relative)		Real Position (Relative)		Time delay (s)
		X (m)	Y (m)	X (m)	Y (m)	
Set 1	Ignition	-7.48	-3.36	-7.87	-3.36	0.8
		-12.49	-3.14	-12.85	-3.13	0.6
		-17.46	-2.90	-17.78	-2.88	0.5
		-22.45	-2.67	-22.96	-2.64	0.8
	Extinction	-10.00	-3.25	-10.54	-3.21	0.8
		-14.93	-3.04	-15.63	-2.97	1.1
		-19.93	-2.78	-20.63	-2.75	1.1
		-24.93	-2.55	-25.74	-2.50	1.3
Set 2	Ignition	-8.51	-2.78	-9.22	-2.73	0.8
		-13.53	-2.51	-13.96	-2.48	0.6
		-18.47	-2.15	-18.99	-2.11	0.7
		-23.48	-1.70	-24.01	-1.65	0.7
	Extinction	-11.00	-2.64	-11.76	-2.62	0.9
		-16.01	-2.35	-16.91	-2.29	1.2
		-20.98	-1.92	-21.63	-1.87	0.9

Mean delay of ignition = 0.7 s Mean delay of extinction = 1.0 s

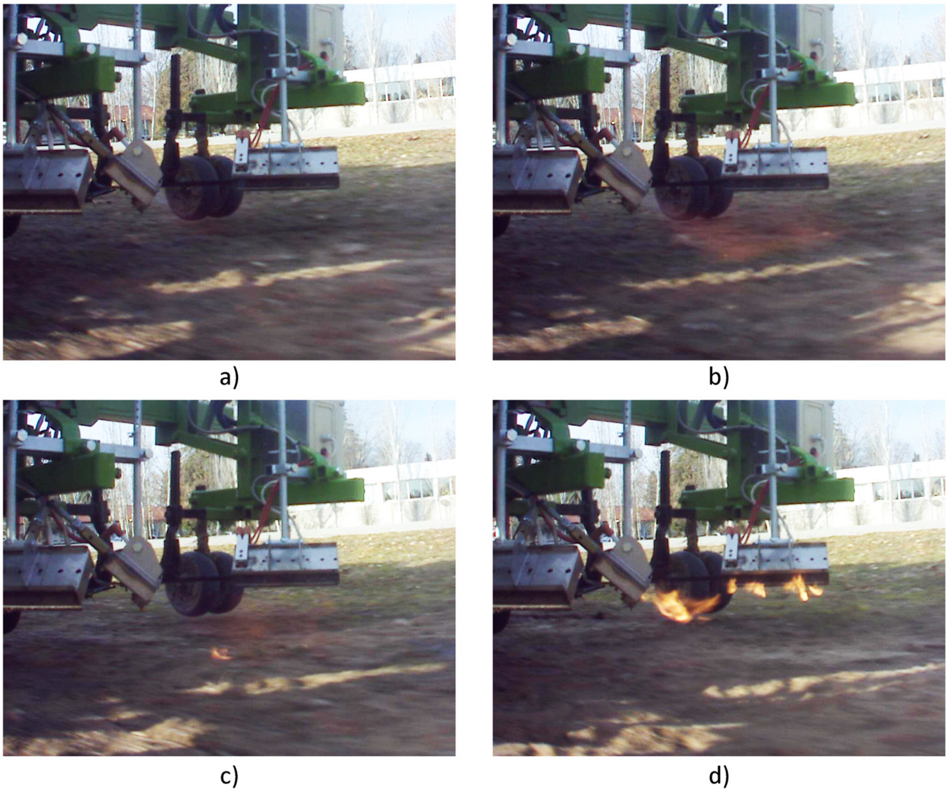


Figure 5.23. Example of the image sequence used for the calculation of the delay of the thermal treatment. (a) Detection of the ignition starting. (b) Detection of flame on the ground. (c) Detection of the withdrawal of the flame. (d) Detection of the total extinction of the burner.

The same criterion used by (Frasconi et al., 2012) was applied to determine in which image the burner could be considered ignited or extinguished. Figure 5.23(a) and Figure 5.23(b) illustrate an example of the ignition process, and Figure 5.23(c) and Figure 5.23(d) show an example of the extinction process. The treatment is considered to begin when the flame makes contact with the soil (See Figure 5.23(b)).

On the other hand, the treatment is considered to end when the flame stops making contact with the soil (See Figure 5.23(c)). Each selected image had an associated GPS position, and the position where the message was sent (desired position) was compared to the position where the action for ignition/extinction was effective (real position) for calculating the associated delay.

With the calculation of the associated delays for both the ignition (0.7 s) and the extinction (1 s) of the burners, the HLDMS can adjust the coordinates where such commands must be sent given an operational speed to increase the effectiveness of the treatment.

5.5.3. Perception/Actuation and Decision Making

With the aim to present a complete working system, a general test that involved the coordination between the perception system and the actuation was executed. Given that the system was designed for selective weed control, this final test was used to assess the ability of the system in performing this task.

The whole agricultural system was scheduled to follow a pre-defined plan along the maize field, consisting of the following four waypoints (See Figure 5.24), which was part of the general mission to be accomplished. The other part of the mission is the execution of the weed control treatment by weed coverage detection, synchronization, and actuation. The primary objective of the mission was to follow

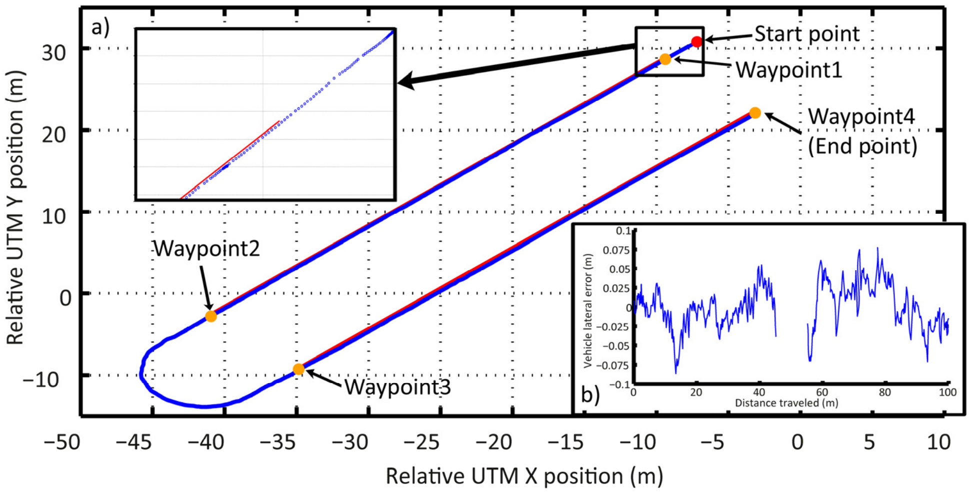


Figure 5.24. (a) The path of the vehicle recorded following the pre-defined mission. (b) Error between the trajectory followed by the vehicle and an estimation of the position of the center line of the central rows for each sector.

the waypoints without putting the crop at risk and to execute an effective treatment in the areas where the weed coverage was higher than the minimum permitted coverage. The HLDMS was in charge of this primary objective, based on the information provided by the perception system with the actuation system.

5.5.3.1. Path Following Test: Deviation Errors

The pre-defined path (the four waypoints - red lines) represents the beginning and end of each pass through the field. The path was selected with a certain degree of uncertainty, i.e., it did not correspond exactly to a centered and parallel line between the two central rows. This represents the mapping proposed in (Auat Cheein et al., 2013; Slaughter et al., 2008). Therefore, the perception system must identify the misalignment of the followed path (line-of-sight) with respect to the row crops. Table 5.6 presents each of the relative UTM coordinates where the crop row detection system generated an output (every 2 m of distance traveled) and the correction parameter over the line-of-sight followed. Sector 1 corresponds to the straight line that connects waypoint 1 with waypoint 2; Sector 2 corresponds to the straight line that connects waypoint 3 with waypoint 4. Figure 5.24(b) illustrates the difference between the trajectory of the vehicle and an estimated position of the center line of the central rows for both Sector 1 and Sector 2.

In this test, the corrections were not made based on the same magnitude as indicated by the crop row detection system but were decreased by a factor related to the phenological stage of the maize plants, given that the width of the plants could affect the precise detection of the rows (for this test, the phenological stage of the maize was between 5 and 7 leaves with collar). This factor was adjusted to decrease the abrupt changes in the heading of the vehicle given the corrections that must be performed; however, the time and distance needed to converge in following the row crops were increased.

Table 5.6. Relative UTM positions where the perception system generated an output correction value.

Sector 1			Sector 2		
Points (Relative UTM)		Correction (m)	Points (Relative UTM)		Correction (m)
X (m)	Y (m)		X (m)	Y (m)	
-6.31	31.86	0.19	-38.17	-12.48	0.24
-7.67	30.47	0	-36.85	-11.22	0.28
-9.08	29.02	-0.11	-35.54	-10.08	0.30
-10.46	27.61	0	-34.29	-8.78	0.22
-11.06	27.01	0	-33.26	-7.82	-0.09
-12.43	25.68	0	-31.80	-6.48	0
-13.89	24.21	0	-30.45	-5.13	0
-15.42	22.68	0	-29.20	-3.86	0
-16.66	21.48	0.06	-27.84	-2.50	0
-18.02	20.13	-0.31	-26.33	-1.02	0.07
-19.46	18.76	0	-24.90	0.38	0
-20.74	17.43	-0.14	-23.60	1.65	0
-22.14	15.98	0	-22.24	2.98	0.11
-23.59	14.56	0	-20.81	4.44	0
-24.92	13.23	0	-19.49	5.70	0
-26.21	11.95	0	-18.12	7.03	0
-27.62	10.52	0	-16.78	8.38	0
-29.00	9.19	0	-15.54	9.65	0
-30.23	7.94	-0.12	-14.14	11.08	0
-31.68	6.49	0	-12.66	12.48	0
-32.94	5.25	0	-11.29	13.87	0
-34.34	3.81	-0.16	-9.86	15.28	0
-35.77	2.40	0	-8.51	16.68	0.06
-37.24	0.88	0	-6.98	18.18	0.09

5.5.3.2. Weed Control Test: Amount of Product Applied in the Treatment

The second part of the mission presented in Figure 5.24 was the execution of the weed control in the maize field by a specialized machine (See Figure 5.6). To do this, each time an image was acquired by the perception system and a weed density matrix was given. This matrix is interpreted by the HLDMS to plan the ignition and extinction of the burners. Each matrix cell contains the weed density information (d_{ij}, subsection 5.5.1.3) of either the left side or the right side of each crop row, in an area of 0.375 m wide by 0.25 m long. Given that the thermal treatment is performed in the intra-row space, the action is executed by each couple of burners. Therefore, the matrix must be processed to define the state of each couple of burners at each instant in time.

Figure 5.25 illustrates the interpretation of the weed matrices and the resultant weed coverage map for the entire mission, when all coverage matrices are joined consecutively. It can be seen that in many cases, the treatment is only necessary in one cell, i.e., in the intra-row space with an area of 0.25 m wide by 0.25 m long, which represents precisely the minimum area defined for treatment. Given the geo-positioning errors, the communication delays, and the electro-mechanical limitations of the entire system (limitations of the perception system, the Main Controller, and the actuation system), it is impossible to accurately fulfill the

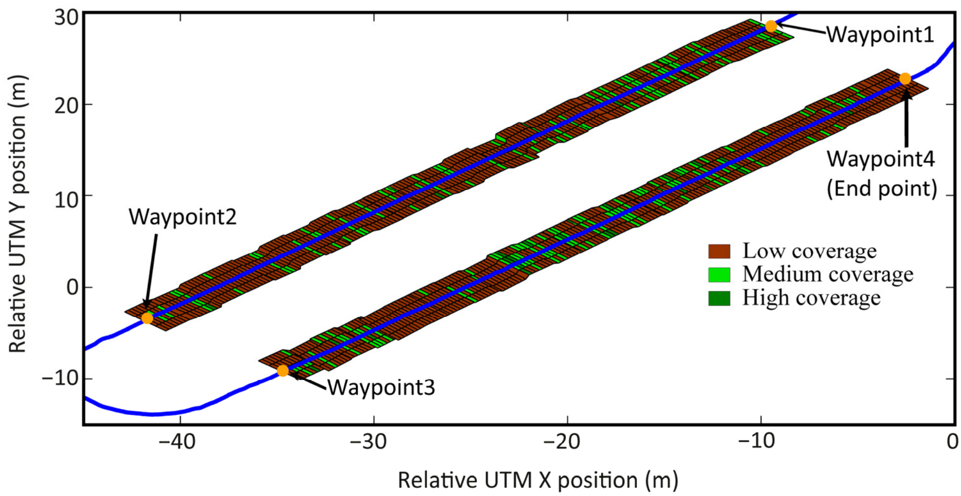


Figure 5.25. Resulting weed coverage map based on the weed density matrices and the interpretation of the three density levels.

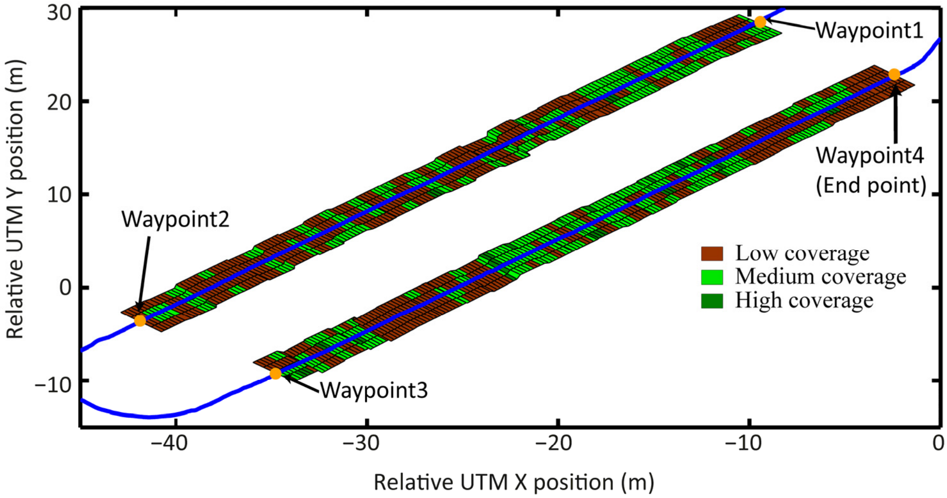


Figure 5.26. Resulting map of the burner's actuation based on the original weed coverage matrices and the delays associated with the ignition and extinction of the burners.

ignition and extinction of the treatment for the worst cases (only one cell). Therefore, to execute an effective treatment, the burners must be turned on early enough to ensure that the desired area is being treated properly. Given the delays calculated in the previous test, the original weed coverage map becomes the map presented in Figure 5.26.

These electro-mechanical and communication limitations lead to the increase in the use of product for weed control (in this case, LPG). Table 7 presents a comparison of the use of product between a hypothetical treatment (Situation 1) following this mission but without the use of the perception system for weed detection (assuming full weed coverage in the entire mission) and the real treatment (Situation 3) executed with the resulting weed coverage map presented in Figure 5.26. Table 5.7 also presents the use of product in a hypothetical treatment (Situation 2) where there are no electro-mechanical and communication limitations.

Table 5.7. Comparison of the use of product for selective weed control.

		Area (m2)	Percentage of the coverage area	Total distance traveled by the four pairs of burners when ignited (Td)	Total operating time of the burners (Tt)	Total consumed product (Kg) (Frasconi et al., 2012)	Percentage of product spared
Situation 1	**Total Burners treatment area**	95.4	-	381.8 m	916.3 s	0.65	-
Situation 2	**Low coverage weed detected**	16.3	17.1%	65.3 m	156.6 s	0.17	85.1%
	High coverage weed detected	1.4	1.5%	5.8 m	13.8 s	0.02	
Situation 3	**Low coverage treated area**	39.1	41%	156.3 m	375 s	0.41	65.1%
	High coverage treated area	2.6	2.8%	10.5 m	25.2 s	0.04	

5.6. Conclusions

The configurations of the perception, the decision-making, and the actuation system have been defined to make up an autonomous vehicle for agricultural applications and, more specifically, for weed control in wide-row crops.

The described perception system has two important tasks: (a) the detection of the crop rows for guiding the vehicle in the field and (b) the detection of weed coverage to perform selective weed control. Based on the tests conducted, the perception system has been shown to be flexible, scalable, robust, and with a suitable level of real-time performance for the application it was designed for.

Commercial devices were used with standard communication protocols for exchanging messages and interaction between them; the system has proven its reliability for a large number of working hours; the processing algorithms have proven to be quite flexible and scalable, with the ability to adapt to different situations for both the system itself and the environment perceived.

The image acquisition and data processing capabilities have been presented, as well as the required times associated with each task performance and the limitations of each system. The errors associated with the integration of information between image acquisition and GPS positions have been characterized, where positioning the weed coverage matrix has an associated error of ±0.08 m, and the lateral displacement of the path followed with respect to the center of the crop rows has an associated error of ±0.03 m. Both errors are perfectly manageable because the actuation system, i.e., the burners, has a working length of 0.25 m, allowing for a certain degree of flexibility in planning, and allows for minor adjustments on where the burners should be turned on and off. Possible future work to improve the geo-positioning of images is the use of an external trigger to synchronize the capture of images, a capability already incorporated in the GPS, the Main Controller, and the camera.

Crop row detection is a crucial task for guidance and weed detection. The proposed method achieves acceptable results with 89 % of successful corrections in path following. Additionally, the high weed detection rate (91 %) verifies the real-time performance of the proposed approach. This has been achieved under different illumination conditions and different crop growth stages, verifying the robustness and efficiency of the whole system.

A lateral-position sensor device has been designed and integrated into the machine for physical weed control to execute the control of the lateral displacement of the implement with respect to the vehicle. The device has proven to be robust enough to work in difficult working conditions (given the amount of dust and water) and with sufficient reliability and accuracy for accurate control. Moreover, the controller designed for executing this task, although it meets the desired characteristics, requires a major adjustment for better rejection of disturbances coming from the contact of the implement with the ground.

The delays associated with the activation of the treatment were computed, i.e., the ignition and extinction of the burners. Given the architecture of the High-Level Decision-Making System and the Actuation Controller, in addition to the electro-mechanical delay of the relays and igniters, both the ignition time delay (0.7 s) and the extinction time delay (1 s) were measured. To ensure an effective treatment, the planning of the activations of the burners must take into account these delays, which leads to a higher amount of applied product. However, the tests conducted have shown that selective treatment remains, and depending on the coverage of the weeds in the field and the proximity between patches of weeds, there may be higher or lower product savings. Future work can focus on improvements to reduce the delays associated with communication between the HLDMS and the Actuation Controller. These two elements can be integrated into the same computer, a capability that can be fulfilled by the current Main Controller.

The integration of the sensors and actuators presented in this chapter has been positively assessed by the RHEA consortium. The experimental results obtained with individual vehicles make the incorporation of this design into a fleet of robots promising, which is the main future objective of the authors.

The proposed architecture, with three main systems, is designed for weed control in maize fields, but thanks to its flexible and open design, the same vehicle can be used for different agricultural tasks. The unique requirement requires the adaptation of new elements and related processes for the intended task. For example, these systems could be used for site-specific treatments in garlic or other crops with different row widths.

Chapter 6

Conclusions and Future Work

6.1. General Conclusions

The concept of fully autonomous agricultural systems, as well as the use of fleet of robots in agricultural tasks, has been gaining increasing attention in the last two decades, thanks to new technologies for autonomous vehicle guidance and autonomous implements. The integration of technological advances in Precision Agriculture has been an important factor driving higher levels of automation in agriculture, although there is still significant work to do. This Thesis presented several developments, derived from the research, that have allowed the configuration and integration of a fully autonomous agricultural system based on a fleet of robots, with specific applications in autonomous weed control. This Thesis covered three main aspects ranging from the development of a simulation environment (Chapter 3), to the development and evaluation of algorithms (Chapter 4), to the execution of tests on real crops under real conditions to demonstrate the capabilities and limitations of the integration of robotics capable of performing autonomous agricultural tasks (Chapter 5).

The work described here focused on weed control applications within the framework of the RHEA project; however, this work can be extended to many other types of agricultural applications.

6.1.1. Simulation Tool for a Fleet of Agricultural Robots

Given the needs to combine robotics and agricultural knowledge, the use of a simulation environment was of great help to take the first steps towards the integration of a fully autonomous agricultural system based on a fleet of robots. The SEARFS simulation environment presented in Chapter 3 was the first main contribution that helped in the implementation of Precision Agriculture techniques, which enables their evaluation in a realistic 3D virtual world. This simulation environment was instrumental in developing an operational fleet of robots for Precision Agriculture that could cooperate and execute a diverse range of tasks simultaneously. The simulation environment also enabled the validation of new control architectures for multi-robot agricultural systems.

6.1.2. Control Architecture and Main Controller for a Fully Autonomous Agricultural System

One of the most important elements that will allow the implementation of a fully autonomous agricultural system is the Main Controller, which can enable communication and integration of the various subsystems (both commercially available units and prototypes) needed for autonomous guidance, site-specific weed control, and safety, among numerous other tasks. A hybrid control architecture with a central frame consisting of a Main Controller based on a cRIO system was found to be best suited for the systems described in this Thesis, where it was imperative for the acquisition of the principal sensory systems to be integrated. This approach allowed the information provided by the sensory system to be merged to improve the overall performance and provide greater accuracy, robustness, and complementary data while reducing the amount of hardware.

The configurations of the perception, the decision-making, and the actuation systems were defined to construct an autonomous vehicle for agricultural applications, especially weed control in wide-row crops. Commercial devices were used with standard communication protocols for exchanging messages between the systems. This approach was proven to be reliable for a large number of working hours, and the processing algorithms were quite flexible and scalable, with the ability to adapt to different situations for both the systems themselves and the environments that they perceived. The integration of the sensors and actuators presented in this Thesis was positively assessed by the RHEA consortium. The experimental results obtained from individual vehicles indicated that the design will be compatible with a fleet of robots, which was the main objective of this work. The proposed architecture incorporating three main systems was designed for weed control in maize fields, but thanks to its flexible and open design, the same vehicles can be used for other agricultural tasks. However, this will require the adaptation of new elements and related processes for the intended tasks. For example, these systems could be used for site-specific treatments in garlic or other crops with different inter-row distances.

Based on the requirements for a fully autonomous agricultural system, a hybrid control architecture was designed based on a centralized controller. Many comments from the RHEA partners and conference colleagues were received throughout the development of the research that questioned the selection of the Main Controller and the design of the architecture. It is interesting to note that most of these comments were related to the choice of not using ROS as a basis for the design of the architecture, the communication systems, and further developments.

Is clear that ROS is a powerful tool for the development of robotic systems that streamlines communication between devices (nodes) either on the devices themselves or a remote site where the software is executed. Another factor that favors the use of ROS is the ability of users to share their developments because there is a fairly large community composed mainly of researchers and students. Sharing codes, drivers, and algorithms, has the potential to greatly reduce the level of work that must be performed to implement new systems. Given the level of integration achieved, ROS seemed to be another option to consider during the design phase.

Even so, by acquiring experience working on the RHEA project and by demonstrating the capabilities and limitations of the architecture through experimental results in real crop fields, it can be concluded that the design of the control architecture, as well as the selection of the Main Controller, was a valid integration approach. Moreover, this Thesis showed that the system performance could be improved in relation to the treatment accuracy and control if some of the external elements (distributed devices) are integrated into the Main Controller. Basically, any task that requires strict runtime compliance (sensor acquisition, data correlation, and actuation) can be integrated into the Main Controller to provide improved execution times and performance, as demonstrated in this Thesis.

Some functions and algorithms unable to maintain a consistent execution time, particularly with respect to image processing, do not take full advantage of the real-time capabilities of the Main Controller. In these cases, to improve the image processing performance and increase the ability to process more images per second, the execution of the algorithms should be performed using dedicated hardware devises rather than the selected Main Controller. However, for this type of application, where a high rate of frames per second in high-quality image processing is not required, it is acceptable to integrate the image processing within the Main Controller, which reduces the amount of hardware, provides better geo-positioning of the images, and enables other systems within the Main Controller to have the images available for executing, e.g., obstacle detection.

In addition to the advantages in the execution of real-time tasks within the Main Controller, other aspects such as robustness, flexibility, scalability, and modularity allow a fully autonomous agricultural system to be integrated and tested in a real environment. Because the integration effort involved several different research groups, each working with a specific programming language (e.g., C++, Matlab, and Python), the selection of the Main Controller was not an impediment for this work, given that LabVIEW was able to integrate and call the external code.

One of the promising features of using the Main Controller for the integration of a fully autonomous agricultural system is the capability for managing diverse programming levels, from the control of analog and digital I/O (aided by a FPGA module) to the implementation of decision making and intelligent control algorithms, as well as image processing and user interfaces, all of which use the same development environment (LabVIEW).

6.1.3. Testing the Control Architecture in a Real System

The control architecture and the Main Controller were implemented in the mobile units of the RHEA fleet, with the objective of performing site-specific weed control in three different scenarios. When working in real field conditions with more than one robot at a time, particularly when each robot is in some way different from the others (this is the case when the GMUs of the RHEA project carry three different implements, as shown in Figure 4.2), the difficulties encountered are larger and more complex than a homogeneous closed-environment multi-robot application. One of the major difficulties when integrating the control architecture in the RHEA units is obtaining a proper setup for each unit. Because a prototype was designed that required many elements and devices to work properly at the same time, the Main Controller was required to robustly manage the communications and failures of the devices. This was achieved thanks to the intrinsic characteristics of the selected cRIO device, consisting of an industrial computer that offered great hardware and software benefits in complex and demanding environments, such as those encountered in this type of application.

One of the advantages of the architecture for integration of the various devices developed by the different partners, was the ability to modify, set, and adjust the parameters and algorithms in real-time. This was enabled by LabVIEW, which generates parallel code for each subroutine or function using a user-friendly interface that can be accesses at runtime operation. However, the use of this interfaces presented a disadvantage in that during wireless communication there were many failures and problems in establishing and maintaining open connections. A conclusion that can be drawn from this experience is that the debugging procedure was not appropriate for the application given the nature and type of connections between the users and the cRIO systems. Nevertheless, after passing the test and debugging processes, the performance of the system was as expected.

With respect to communications and data sharing between devices in the network and/or routines in one device, experience has taught us that a simple communication protocol allows us to maintain greater control and adequate performance of the system. For example, a major benefit of LabVIEW is the communication between real-time processes within the Main Controller, although this was not always the case with respect to communication between other devices running LabVIEW. Hence, the RHEA communication protocol for monitoring and controlling the fleet at the base station gave us greater benefits than the network-sharing LabVIEW variables. In addition, the drivers needed for communication with the COTS devices, such as cameras, GPS receivers, and lasers, were already available and required very few modifications to be made to suitable for the application thanks to the developer community and specialized libraries.

6.2. Specific Conclusions

Below, the specific conclusions for each objective proposed in this Thesis are presented in detail, starting with the most relevant from the scientific stand point.

6.2.1. Conclusions Regarding Accuracy in Vehicle Guidance and Agricultural Treatment Aplication

6.2.1.1. Vehicle Guidance in Wide-Row Crops:

Based on the perception system presented in Chapter 5, an algorithm for crop-row-following was implemented and tested in the mobile units of the RHEA project. This algorithm consists of adjusting an original straight line that crosses the field (given by the mission that was planned in advance), and minor corrections made using the perception system. It was possible to obtain an average error of approximately ±5 cm when following the crop rows, which is slightly higher than the proposed error (±2 cm) as a specified in the RHEA project requirements. Nevertheless, neither the vehicle nor the implement caused any damage to the crops on any occasion and successful detection was performed in approximately 89 % of the cases. Given the complexity of the system, various elements affected the performance of the controller, as described below.

a) **Camera arrangement:** Because the arrangement of the camera on the tractor (Romeo et al., 2013) was a considerable height and distance from the crop rows (See Figure 5.4), the accuracy of the calculation of the lateral displacement of the vehicle relative to the crop was slightly higher than in other applications where the camera was only a few centimeters above the ground, we did not observe the ±2 cm error proposed. Additionally, the camera arrangement significantly affected the accuracy of calculating the difference in the angle between the vehicle and the crop because this information is given by the farthest pixels in the ROI in the longitudinal axis (which did not contain the same amount of information as the pixels that represent the ROI area closest to the vehicle).

b) **Crop growth status:** Due to the procedure for crop row detection (Guerrero et al., 2013), if the crops are small in size, the precision of the calculation of the position of the crop with respect to the vehicle is higher. Thus, if the crops are in their early growth state (the first moments where such mechanical-thermal control can be performed), the occupation of the crop in the images (the width of the plants) is less than if the crop is in a later growth state (i.e., 5-7 leaves with a collar for maize).

c) **Geo-referencing an image:** Given the procedure used to associate a GPS position with an image and due to the corrections that the path follower controller must perform (generating considerable oscillations in the heading; See Figure 5.12), the calculation of the difference between the center of the crop rows with respect to the center of the vehicle may be significantly altered on some occasions (as demonstrated by the worst case error of approximately ±0.08 m).

To summarize, several factors were identified that affect the perception capacity and the actuation system for guiding an autonomous vehicle into a crop field. Depending on the situation, this may affect the maximum error. Nevertheless, given the application in which the system was tested (a maize field seeded at 75 cm, with a known position for the start and the end of the field and an approximate location of some of the crop rows), the vehicle characteristics and the width of the mechanical treatment, the real accuracy obtained was sufficient to meet the specific objective of keeping the crops safe (i.e., free from damage).

6.2.1.2. Lateral Displacement Accuracy of an Implement for Physical Weed Control:

A control system for a specific implement for physical weed control was designed, developed, and tested, as presented in Chapter 5. A specialized sensor was developed to measure the lateral displacement of the implement with respect to the vehicle. This system was validated using a Laser as an external measurement device, obtaining a precision of approximately ±0.004 m. Based on this sensor system and the actuation system consisting of a hydraulic cylinder acting on a steering wheels, a set of two PID controllers in a cascade configuration was implemented. A series of tests were performed by tuning the controller, to obtain an error of approximately ±0.01 m and a stabilization time of approximately 3 s at 0.28 m/s. Additionally, setting up this system was not an easy task, given the complexity and dynamics of the interaction between the vehicle, the implement, and the ground, which caused the implements to oscillate slightly around the desired position. Nevertheless, the magnitudes of oscillation were approximately 2 or 3 cm, which are small given the size of the implement, the associated errors in the vehicle guidance, and the gap between the mechanical element (the hoe) and the crop. Although the errors obtained were larger than the proposed error (0.5 cm), the crops remained safe.

6.2.1.3. Savings for an Implement for Physical Weed Control:

A control architecture for autonomous agricultural systems was designed and implemented in the mobile unit of the RHEA project. This control architecture allowed the integration of a perception, an actuation, and decision-making subsystems for a fully autonomous agricultural system configured for physical weed control in maize. The implement used for the assessment of the control architecture consisted of four pairs of burners for thermal weed control within the intra-row space and specialized mechanical elements for treating the inter-row space. A characterization of the system was made considering the intrinsic delays in the activation of the burners (relays and valves) and delays in communications. For these tests, the GMUC of the RHEA project was used as a control system for the implement. The results are presented in Chapter 5, where three situations (common usage, ideal, and real) are analyzed, for a specific field with a specific weed distribution, saving 65.1 % of product (propane). Two interpretations can be extracted from these results.

1) The delays are higher than expected, which considerably affects product savings. The delays in communication between the Main Controller and the Actuation Controller can be reduced to almost a tenth of a second if another type of communication is used or if the control of the valves and relays are centralized in the Main Controller, as proposed in Chapter 4. This can reduce the delays in the ignition and extinction of the burners to about half the current values. Performing the same analysis as presented in Table 5.7, we can obtain a savings of approximately 73.5 % (See Table 6.1), which is a value that is very close to the stated objective.

2) The spatial distribution of weeds in the field is a factor that significantly affects product savings given the non-ideal characteristics of the actuation system (relays and valves). This forces the burners to be set in advance with respect to the edge of the weed patch and for their shut down to be delayed with respect to the end of the weed patch. Thus, the product savings are a function of the patch size and distribution (e.g., dimensions, distance between patches).

The process by which weeds spread in a field is very complex given that weeds are living organisms that interact with the soil and weather. Thus, weed spreading is difficult to simulated and express mathematically, as discussed in Chapter 3.

Table 6.1. Extension of Table 5.7 regarding the use of product for selective thermal weed control.

<table>
<tr><th></th><th></th><th>Area (m2)</th><th>Percentage of the coverage area</th><th>Total distance traveled by the four pairs of burners when ignited (Td)</th><th>Total operating time of the burners (Tt)</th><th>Total consumed product (Kg)</th><th>Percentage of product spared</th></tr>
<tr><td rowspan="2">Situation 4</td><td>Low coverage treated area</td><td>29.4</td><td>30.8%</td><td>117.5 m</td><td>282 s</td><td>0.31</td><td rowspan="2">73.5%</td></tr>
<tr><td>High coverage treated area</td><td>2.2</td><td>2.3%</td><td>8.8 m</td><td>21 s</td><td>0.03</td></tr>
</table>

6.2.2. Conclusions Regarding the Extension of the Control Architecture

A control architecture was developed and implemented for individual robots and robots working in fleets to improve reliability, decrease complexity and cost, and permit the integration of software from different developers. The Main Controller, which was the nucleus of the architecture, allowed the direct incorporation of a large number of modules as well as the expansion of their data acquisition, control, and communication capabilities. This includes the following capabilities.

1. Ethernet: available NI WLAN modules and Ethernet switch.
2. Laser: connected through Ethernet or NI specific modules.
3. Industrial communication buses: a CAN bus and an ISO bus can be integrated through the NI CAN interfaces.
4. Inertial Measurement Units: connected through NI serial modules.
5. General I/O modules: NI analog and digital I/O modules.

Another quality of the controller is the ability to incorporate a slave chassis to expand the capacity to add more modules in a different physical space for the Main Controller, which allows the modules for controlling an agricultural implement to be placed on-board. The expansion chassis communicates with the Main Controller via EtherCAT, which is an open high performance Ethernet-based fieldbus technology commonly used in industrial automation.

Chapter 4 presented the evolution of the RHEA computing system based on the control architecture, which was proven to be flexible and robust, while maintaining real-time performance for the various integrated elements in the architecture (both within the Main Controller and in the distributed devices).

6.2.3. Conclusions Regarding the User Control and Safety of the System

Chapter 4 presented the development and implementation of a user interface for controlling and monitoring the fleet of robots. This interface, together with the communication routines implemented into the Main Controller (See Chapter 5, subsection 5.4.1), allowed the status and location of each unit to be monitored and the motion of the vehicles to be controlled (starting, stopping, or pausing). In addition, the user can load a predefined mission to each unit and record its GPS position.

Another element developed and implemented for maintaining the safety of the system was a collision avoidance algorithm (See Chapter 4, subsection 4.5.3). This safety algorithm added a cooperation element in the fleet of autonomous agricultural robots.

6.2.4. Conclusions Regarding the SEARFS Simulation Environment

The development of a simulation environment for the fleet of robots designed for Precision Agriculture was presented in Chapter 3. This simulation tool, named SEARFS, was based on two powerful computational COTS systems (MATLAB and Webots). SEARFS enabled the visualization and evaluation of the execution of the agricultural tasks by the agricultural robots equipped with various perception and actuation mechanisms. This evaluation was performed using 3D virtual world visualization to represent the real characteristics of a defined field location (obtained by measurements or downloaded through online databases) for modeling different variabilities that may affect the task performance accuracy of the fleet of robots.

The SEARFS environment was proven to be a useful tool for validating the design concepts involved with ground and air vehicles. It was also an exceptional tool for mission analysis with fleets of robots in the RHEA project. In addition, this simulation environment was able to integrate with new elements by introducing and testing new communication protocols (communications between the Main Controller and the peripherals of the RHEA ground mobile unit), by simulating virtual crop fields for machine-vision analysis and setup (Guerrero et al., 2012), and by adding new autonomous implements, vehicles, and controllers for evaluation of its capabilities, while allowing a better understanding of its usage (Emmi et al., 2012).

6.2.5. Final Remarks

The control architecture, methods, procedures and algorithms presented in this Thesis, resulting from the research developed, have been tested, verified, and positively assessed in a qualitative and quantitative manner. In May 2013, the ground mobile fleet was completed. All of the hardware and software were installed. Since then, the fleet (equipment and algorithms) has been tested and improved almost daily (approximately six hours a day, five days a week, four weeks a month, for approximately 11 months) with an estimated duty cycle of approximately 33.33 %. That means an estimated total working time of approximately 440 hours. During this period, the fleet was tested in three different real scenarios at the CSIC-CAR facilities in Arganda del Rey, Madrid (featuring, e.g., dust, mud, wind, rain, different light conditions), demonstrating step by step reliability with a 2-minute interval between failures (the longest, continuous video we could take in July 2013 was 2 minutes long) to approximately 2 hours of continuous work with minor problems (achieved in the final RHEA project demonstration on May 21, 2014). We did not precisely record the fleet working time and contingencies because they were clearly outside the scope of this work. A final demonstration was performed on May 2014, for the full fleet of robots assessment with success.

6.3. Future Work

This Thesis presented a number of contributions for the configuration and integration of a fleet of autonomous robots designed to perform agricultural tasks. However, there remains a lot of work to be done to bring these contributions to industry.

The simulation environment presented in this Thesis has great potential that has not been fully exploited. The ability to integrate new robot models (both vehicles and implements), while simulating diverse terrain, means that SEARFS will be a powerful tool for future developments. One of the first studies that should be performed with SEARFS should be the implementation of several models for weed spatial distribution (knowing that such models may resemble the reality, but not represent it faithfully). With a better characterization of the RHEA implements, a more extended evaluation of the ability to save product can also be performed. The design and implementation of diverse RHEA robots has already been performed using the Webots simulation tool. Some controllers and control strategies for vehicle guidance and implement control have already been developed to continue the evaluation and improvement of the system. Agriculture is a complex science, and we will first require many different models in the system (seasonality, treatment effectiveness, and cost-benefit) to be able to simulate economic scenarios for different agricultural robot systems.

The control architecture presented in this Thesis has proven to be quite useful, efficient, and robust for controlling autonomous vehicles in agricultural tasks. However, further testing is needed, especially in other applications beyond weed control. There are still many agricultural tasks that can be exploited, from preparing land for cultivation to harvesting, where some progress has been made with respect to automation. The next step will be a completely automated agricultural vehicle containing implements and hardware approaches that remove performance limitations that introduces delays in communications. One important improvement will be centralization of the critical tasks (such as control and guidance of the vehicle and implement). This work could help to debug designs and bring automated agricultural products to industry.

With regard to the use of various robots for performing agricultural tasks, the control architecture presented in this Thesis has proven its utility when cooperation is needed. The use of multiple robots remains an untapped approach for both heterogeneous and homogeneous tasks. Future work will focus on increasing the capabilities of the Main Controller for restructuring the original mission if needed, increasing the efficiency, improving the cooperation, and enabling better obstacle detection. In addition, remote connections from other parts of the world will allow the fleet of robots to be supervised by experts in the field.

Part II: Summary in Spanish

1. Introducción

En los últimos 50 años la población global se ha duplicado mientras que la tierra cultivable sólo se ha incrementado en un 12 %. Aun así, según un informe anual de la Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO) (FAO, 2012), la producción global de cultivo se ha expandido el triple en el mismo período de tiempo gracias a un mayor rendimiento por unidad de tierra y mayor intensificación en el cultivo. Uno de los elementos importantes que ha permitido este incremento en la producción agrícola mundial ha sido un mayor uso de fertilizantes y pesticidas. No obstante, el uso abusivo de estos insumos agrícolas puede generar resultados negativos en el medio ambiente y en la salud de los humanos y animales. El enfoque más recomendado para el correcto uso de pesticidas y fertilizantes se conoce como Gestión integrada de Plagas o IPM (*Integrated Pest Management*), que consiste principalmente en el uso de información de la población de las plagas para estimar pérdidas y en consecuencia ajustar la dosis de intervención. IPM es un enfoque ecológico, económicamente hablando, justificado para la gestión del cultivo que reduce y minimiza el riesgo tanto para la salud de los humanos como del medio ambiente, hace hincapié en el crecimiento de un cultivo saludable con la menor perturbación posible sobre los agro-ecosistemas e incentiva el uso de mecanismos naturales de control de plagas (FAO, 2012).

A pesar de que IPM es una técnica eficiente para la reducción del uso de pesticidas mientras que mantiene una alta productividad, dicha técnica considera principalmente el desarrollo, evolución y tipo de infestación en el tiempo (ejemplo de esto es el comportamiento y ciclo reproductivo de las plagas y las respuestas de patógenos de plantas al clima y a la temporada) en un campo completo. De todas maneras, en la década de los 70 y los 80, surgieron nuevas metodologías que ayudaron a los investigadores a entender de mejor manera las condiciones de variabilidad de la tierra y el cultivo en el campo (Robert, 2002). Una de las consecuencias más importantes, como resultado de este nuevo conocimiento, fue la capacidad de percibir el potencial beneficio de la gestión del cultivo por zonas dentro del campo en contraposición a la gestión de todo el campo por igual, tal y como se aplican las técnicas de IPM.

Se han otorgado varios nombres a este tipo de práctica (Cook et al., 1998; Murakami et al., 2007), incluyendo gestión del cultivo por tratamiento específico localizado, labranza específica localizada, labranza de precisión. De todas maneras, el rango de metodologías cuyo propósito es optimizar la gestión de los campos agrícolas es comúnmente conocido como Agricultura de Precisión, y se enfoca en la mejora de la gestión agrícola en tres áreas principales: conocimiento del cultivo, protección del medio ambiente y economía. La Agricultura de Precisión es un concepto de gestión de la agricultura que depende de la observación y la respuesta a las variaciones o variabilidades en el campo. Dicho concepto tiene como base el uso de las tecnologías modernas, tales como los sistemas de posicionamiento global o GPS (*Global Positioning Systems*), los sistemas de información geográfica o GIS (*Geographic Information Systems*), microcomputadores, control automático, detección remota y en el campo, informática móvil, procesamiento avanzado de la información y telecomunicaciones, los cuales ofrecen en conjunto grandes beneficios en la adquisición, procesamiento y la utilización de la información espacial del campo con el propósito de aplicar dichos principios para la gestión de la variabilidad en el campo del suelo y el cultivo (Zhang et al., 2002).

Para gestionar la variabilidad/imprevisibilidad en el campo, y gracias a los nuevos avances en sensores, entre los que destacan visión por computador y sistemas de control en las últimas dos décadas, han surgido múltiples líneas de investigación con la idea de desarrollar robots agrícolas para cultivar, cosechar y llevar a cabo el control de plagas (Mousazadeh, 2013). Dichos sistemas autónomos permiten que la adquisición de la información del campo sea más certera (Lee et al., 2010), que el control automático de las malas hierbas sea más efectivo para garantizar la seguridad del cultivo (Bakker, 2009; Tian, 2002), y que la cosecha y la trasplantación sea más precisa y eficiente (Nagasaka et al., 2009; Pilarski et al., 2002).

Si nos centramos en los sistemas móviles autónomos orientados a la gestión y tratamiento del cultivo o del terreno por localización específica, podemos analizar el problema dividiendo una unidad robótica en dos elementos principales: el elemento que le da movilidad al sistema agrícola (el vehículo), y el elemento que ejecuta el tratamiento (el implemento). Un vehículo autónomo, tal como un tractor comercial modificado, plataformas especializadas o vehículos pequeños, se encarga de guiar al sistema agrícola en el campo de cultivo con el propósito de ejecutar una tarea específica (como por ejemplo cosechar, escardar o controlar las malas hierbas), que se realiza por el implemento autónomo. Dado lo complejo de la tarea, ambos elementos deben trabajar en concordancia y sincronía, y se requiere un gran número de sensores y actuadores especializados para cumplir con la tarea dada en un entorno determinado (como por ejemplo campos al aire libre o áreas de trabajo semi-estructuradas). Esta integración de un vehículo autónomo con un implemento autónomo, además de los sistemas sensoriales, de actuación y de toma de decisiones, es lo que se puede definir como **un sistema agrícola totalmente autónomo.**

Dada la naturaleza de la agricultura, el vehículo debe exhibir robustez, fiabilidad y flexibilidad, y debe ser capaz de ser utilizado en todo tipo de trabajos agrícolas, incluyendo el control de malas hierbas, que es el área en la que se enfoca este trabajo de investigación. Por lo tanto, en términos generales, un mismo vehículo puede ser utilizado para ejecutar diferentes tareas agrícolas dependiendo del implemento que lleve acoplado. Mediante la realización de una revisión de trabajos de investigación desarrollados en años recientes relacionados con la solución del problema del guiado autónomo, en otras palabras, en relación a la automatización y control de un vehículo agrícola, encontramos en la literatura una intensa actividad de investigación (Keicher et al., 2000; Li et al., 2009; Reid et al., 2000). Por otra parte, se puede encontrar una cantidad considerable de actividad de investigación relacionada con implementos inteligentes para el control de malas hierbas (Comba et al., 2010), y que es parte de todos los desarrollos en implementos autónomos para tareas agrícolas en general. Sin embargo, sólo pocos intentos se pueden encontrar en la literatura científica para establecer un sistema agrícola totalmente autónomo mediante la integración de un vehículo autónomo y un implemento autónomo. Muchos autores coinciden en que éste es el futuro de la automatización en la agricultura (Auat Cheein et al., 2013; Bergerman et al., 2012; Johnson et al., 2009; Noguchi et al., 2011; Vougioukas, 2012), donde un único sistema o un grupo de sistema robóticos totalmente autónomos realicen las tareas agrícolas más arduas, permitiendo que el operario se centre en la planificación y la supervisión más que en el guiado del tractor o el control del implemento. Se ha demostrado que estas tareas pueden ser ejecutadas con una mayor precisión por sistemas robóticos que por un operario humano con un incremento significativo en la productividad (Moorehead et al., 2012).

Realizando una revisión general en la literatura científica, se identifican dos enfoques claros para la selección de la morfología de un sistema agrícola totalmente autónomo:

1. **El enfoque de los robots pequeños:** que es el más abundante en la literatura, y que consiste en plataformas móviles o tractores muy pequeños. Estos tipos de vehículos tienen la ventaja de ser más precisos que máquinas más grandes, dado

que poseen una mayor maniobrabilidad y una mayor capacidad para llevar a cabo el tratamiento selectivo en áreas pequeñas. Además, los vehículos pequeños son más ligeros que los vehículos más grandes, proporcionando ahorro de energía en movilidad y reducción en la compactación del suelo. Por el contrario, este tipo de vehículos tienen un ritmo de trabajo más bajo, lo que requiere más horas de trabajo o más vehículos para la ejecución de la misma actividad. Otra desventaja es la falta de robustez, por lo que son incapaces de realizar trabajos muy exigentes durante largos períodos de tiempo bajo condiciones muy exigentes, que requieren máxima atención (es decir, en presencia de piedras, zanjas, árboles, etc.).

2. **El enfoque de los robots de mediano tamaño:** que consiste mayormente en el uso de tractores comerciales modificados, que pueden llevar implementos más pesados y que son capaces de trabajar áreas más extensas que los vehículos de menor tamaño. Debido a que los tractores comerciales vienen de fábrica con elementos estándares controlados electrónicamente (conexiones como el enganche de tres puntos, energía hidráulica y eléctrica, y la toma de fuerza), sólo se necesitan algunas modificaciones para que el tractor pueda operar de forma autónoma. Otra ventaja de la utilización de vehículos de gran tamaño es la robustez intrínseca de los tractores comerciales, permitiendo que el vehículo mantenga una alta tasa de trabajo independientemente de las condiciones ambientales y del terreno. Por el contrario, este tipo de vehículos requieren más elementos de seguridad debido a su tamaño y potencia, y debido al potencial daño que pueden hacer sobre el terreno o el cultivo por compactación.

La gran mayoría de estudios han servido para diseñar y desarrollar nuevos algoritmos y nueva maquinaria especializada, donde la mayor parte de ellos se centran exclusivamente en elementos clave de lo que sería un sistema agrícola totalmente autónomo (por ejemplo, guiado, la detección del cultivo o malas hierbas, y tratamiento selectivo). Por otra parte, varios autores han presentado enfoques conceptuales de las arquitecturas de hardware/software para el establecimiento de un sistema agrícola totalmente autónomo (Auat Cheein et al., 2013; Bakker et al., 2010a; Blackmore et al., 2001; Fountas et al., 2007; Katupitiya et al., 2007; Rovira-Más, 2010a), y sólo algunos de ellos han logrado implementar una integración plena de un sistema agrícola autónomo y probado bajo condiciones del mundo real (Bergerman et al., 2012; Blackmore et al., 2004; Johnson et al., 2009; Kohanbash et al., 2012; Moorehead et al., 2012; Nørremark et al., 2008; Pilarski et al., 2002). Además, éste es uno de los caminos que se deben seguir para poner en práctica (en campos reales y para los agricultores) la integración de la gran cantidad de tecnologías y desarrollos generados en los últimos años para la aplicación de las técnicas de agricultura de precisión. Esta integración demostrará las capacidades que un sistema agrícola totalmente autónomo, o un grupo de ellos trabajando en conjunto, ofrece para un mejor uso de insumos en la agricultura moderna.

Más aún, teniendo en cuenta la necesidad actual de una aplicación más eficiente de productos químicos y técnicas de mecanización para incrementar la productividad, reducir el daño e impacto sobre el medio ambiente y preservar la salud de los seres humanos y los animales, este trabajo de tesis se centra en el estudio de cómo se pueden aplicar los diferentes elementos que permiten la ejecución de técnicas de agricultura de precisión a la vez que unificarlos e integrarlos mediante el uso de robots móviles, con un enfoque especial en la reducción del uso de productos para el control de malas hierbas en cultivos intensivos. Teniendo en cuenta ambos enfoques para la morfología de lo que debería ser un sistema agrícola totalmente autónomo (robots de pequeño tamaño o plataformas, o robots de mediano tamaño o tractores), la investigación plasmada en este trabajo de tesis presenta una arquitectura hardware/software orientada hacia la solución del problema de integración del segundo enfoque. La selección de un número diverso de componentes y de los elementos que constituyen esta arquitectura fue orientada hacia la introducción de un sistema agrícola totalmente autónomo en la industria.

Utilizando el enfoque anterior, este trabajo de tesis presenta una propuesta de investigación en el campo de la navegación autónoma y el control para unidades móviles e implementos aplicados a la agricultura de precisión e investiga las arquitecturas y metodologías más adecuadas para campos agrícolas desde el punto de vista de la automatización.

Un aspecto importante en la constitución de una unidad robótica capaz de ejecutar tareas agrícolas es la capacidad de integrar los conocimientos agrícolas necesarios. Por lo tanto, el primer paso en este trabajo de tesis es el desarrollo de un entorno de simulación que permite la integración de la robótica con la agricultura. Después de desarrollar el entorno de simulación, se ha diseñado una arquitectura hardware implementada para vehículos autónomos móviles que colaboren como una flota de robots en tareas agrícolas que reúna básicamente fiabilidad del hardware, verdaderas características de *plug-and-play* y requisitos de flexibilidad en la programación de los diferentes dispositivos, así como modularidad, capacidad de expansión, ergonomía, mantenimiento y requisitos de coste, que también son de suma importancia de cara a aumentar el número de posibles aplicaciones reales en la agricultura para el uso de una flota real de robots autónomos. El último paso en el desarrollo de esta investigación es la selección, la ordenación, la integración y la sincronización de varios sistemas para constituir un sistema agrícola totalmente autónomo. Por otra parte, este trabajo de tesis presenta resultados experimentales que se utilizan para evaluar la arquitectura hardware diseñada a través de análisis cuantitativos y cualitativos asociados tanto con la reducción del elemento hardware así como la minimización en el desarrollo de software en un único sistema agrícola, totalmente autónoma. Además, en este trabajo se presentan los resultados de un algoritmo para la prevención de colisiones, que fue desarrollado para permitir la evaluación de los beneficios de la reducción de hardware en una flota de robots agrícolas para la ejecución de tareas cooperativas. Por otra parte, este trabajo presenta estos resultados experimentales para demostrar el éxito y el rendimiento del sistema integrado en tareas de guiado del vehículo y control de malas hierbas en un campo de maíz real, además de verificar su utilidad y eficacia.

- **Motivación y alcance**

En los últimos 20 años se ha producido una gran cantidad de avances significativos en las áreas de detección de malas hierbas, guiado de precisión y tratamiento selectivo. Sin embargo, muchos de estos estudios sólo se han centrado en el desarrollo y en la puesta a punto de un único elemento de todo el sistema. Como se ha presentado en la sección anterior, existe una clara necesidad para la integración de todos estos elementos (adquisición, guiado, toma de decisiones y actuación) para establecer un sistema agrícola totalmente autónomo. Una de las motivaciones del trabajo descrito en esta tesis es presentar una alternativa para la selección, ordenación, integración y sincronización de estos elementos para constituir un sistema autónomo completo para aplicaciones agrícolas. Los elementos que se requieren para componer un sistema de este tipo provienen de diferentes áreas de investigación y de diversos grupos de investigación. Por lo tanto, la tarea de integración requiere un enfoque multidisciplinario, en el que cada disciplina tiene que trabajar con diferentes tecnologías, sistemas operativos, lenguajes de programación, metodologías, etc.

El concepto de un sistema agrícola totalmente autónomo, además de la idea de utilizar múltiples robots para mejorar el cometido de algunas tareas no es nuevo. Actualmente algunas universidades, grupos de investigación y empresas pequeñas y grandes, ayudadas por grandes proyectos financiados por la Comunidad Europea y determinados países con altos desarrollos tecnológicos, están buscando soluciones para poner en práctica este concepto. Destacan dos proyectos significativos en este sentido: *Robot Fleets for Highly Effective Agriculture and Forestry Management* (RHEA) financiado por la Unión Europea a través del Séptimo Programa Marco y del proyecto *Integrated Automation for Sustainable Specialty Crops Farming* financiado por el Departamento de Agricultura de los Estados Unidos (USDA).

El proyecto RHEA se centra en el diseño, desarrollo y evaluación de una nueva generación de sistemas automáticos y robóticos para una gestión efectiva de malas hierbas tanto química como mecánicamente, que es aplicable tanto a la agricultura y la silvicultura (Peruzzi et al., 2011; RHEA, 2014). Por el contrario, el proyecto financiado por el USDA se centra en el desarrollo de tractores no tripulados, que son plataformas ideales para las tecnologías de agricultura de precisión, para la captura de información de las copas de los árboles que se utilizarán para la pulverización específica de árboles individuales, para la estimación de los rendimientos de la fruta, y la detección de brotes de enfermedades en los árboles (NREC, 2014). Por lo tanto, otra de las motivaciones de esta investigación consiste en presentar un enfoque para la integración de diversos elementos que hacen posible un sistema agrícola totalmente autónomo, siguiendo el enfoque de los robots de tamaño mediano, que es un compromiso claro por parte del proyecto *Integrated Automation for Sustainable Specialty Crops Farming*[1] y del consorcio RHEA[2].

La evaluación de la arquitectura propuesta se ha llevado a cabo utilizando la flota completa del proyecto RHEA, que proporciona equipos reales (tres tractores automatizados, visión por computador, sistemas de localización, sistemas de detección de obstáculos y tres diferentes implementos agrícolas automatizados) para la realización de pruebas en el mundo real. Esto ha proporcionado una ventaja esencial, lo que permite centrarnos en la investigación, prueba y validación de

[1] Los socios que participan en este proyecto son The National Robotics Engineering Center, John Deere, la Universidad de Florida y la Universidad de Cornell.

[2] Los socios que participan en este proyecto son Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC), CogVis GmbH, Forschungszentrum Telekommunikation Wien Ltd. (FTW), Cyberbotics Ltd, Università di Pisa, Universidad Complutense de Madrid, Tropical, Soluciones Agrícolas de Precisión S.L., Universidad Politécnica de Madrid (UPM), AirRobot GmbH & Co. KG, Università degli Studi di Firenze, IRSTEA, Case New Holland Industrial N.V., Bluebotics S.A., CM Srl.

algoritmos y métodos para la navegación y el tratamiento selectivo en lugar de trabajar en el desarrollo de equipos individuales.

El tipo de aplicación y el entorno en el que el sistema agrícola totalmente autónomo tiene que interactuar definen un problema específico de navegación y actuación. Algunos estudios han desarrollado plataformas móviles o tractores autónomos pequeños, donde la arquitectura de control ha sido adaptada para una aplicación específica y en algunos casos se puede ampliar a otros sistemas. Normalmente, estos robots son plataformas de pequeño tamaño, y ejecutan el tratamiento en áreas pequeñas en el campo simultáneamente (por ejemplo, el espacio debajo de la plataforma). Ante este escenario actual, es necesario tener en cuenta si alguna de estas arquitecturas resuelve el problema tratado en la investigación que da lugar a este trabajo de tesis. Por lo tanto, otra de las motivaciones relacionada con dicha investigación es la oportunidad de poner en práctica la arquitectura de control desarrollada en un campo real, orientada hacia la ejecución de tareas de precisión para el control de malas hierbas.

El alcance de la investigación realizada, que coincide con el alcance del proyecto RHEA (Gonzalez-de-Santos et al., 2012; Peruzzi et al., 2011), es el desarrollo de nuevos conceptos de robótica para la construcción de una flota de robots autónomos con el fin de disminuir el uso de fertilizantes, herbicidas y otros pesticidas mediante la aplicación de productos químicos siguiendo los principios de la agricultura de precisión. Además, parte del alcance de los desarrollos plasmados en este trabajo de tesis es el desarrollo de una arquitectura de control que consiste en sistemas de percepción, actuación, localización y unidades móviles de diferente naturaleza trabajando completamente sincronizados. Esto se puede lograr mediante una red de comunicación y localización implementando interfaces con verdaderas características y control en tiempo real de los dispositivos de percepción, dispositivos de actuación y de las plataformas móviles. Esta arquitectura de control se basa en los principios de inteligencia artificial para decidir qué proceso utilizar, y dónde aplicar la dosis óptima. Este controlador toma decisiones en función de sus entradas: datos del sistema de percepción y el historial de la misión del campo.

2. Objetivos de la investigación

Utilizando el enfoque anterior, esta tesis presenta un estudio en el campo de la navegación autónoma y el control de vehículos e implementos agrícolas orientados hacia la agricultura de precisión, investigando las arquitecturas y metodologías más apropiadas para entornos agrícolas. Por lo tanto, **su objetivo principal es el desarrollo de una arquitectura de control (hardware/software) capaz de integrar elementos sensoriales, de actuación y de toma de decisiones para establecer un sistema agrícola totalmente autónomo como parte de una flota real de robots, con el propósito principal de realizar tareas de control de malas hierbas en posiciones localizadas y disminuir el uso de insumos agrícolas.** Esta arquitectura de control está caracterizada por su robustez (mantener un alto rendimiento bajo condiciones dinámicas) y flexibilidad (permitiendo fácilmente la adición de nuevos elementos sensoriales y de actuación) para facilitar su desempeño en tareas de tiempo real y trabajo de alta precisión en la tarea de actuación. Además, la arquitectura de control propuesta se integra y se prueba en una flota real de robots que ofrecen autonomía completa de la flota de vehículos capaces de viajar a una velocidad de entre 3 y 6 Km/h en campos de cultivo durante la ejecución de diversas tareas agrícolas autónomas (aplicación de herbicida, control mecánico de malezas, etc.).

Esta arquitectura se evaluó inicialmente en un entorno de simulación para flotas de robots aplicados a agricultura, que se ha desarrollado como parte de este trabajo de tesis, y más tarde se puso a prueba en condiciones reales utilizando una flota de robots autónomos.

Los objetivos específicos planteados en la investigación son los siguientes:

1. Estudiar y aplicar algoritmos para el seguimiento de líneas de cultivo por parte de los vehículos agrícolas autónomos utilizando la información proporcionada por un sistema de percepción (consistente en visión artificial y GPS) como entrada. El objetivo durante la navegación es seguir las líneas de cultivo con una precisión de aproximadamente ±2 cm para garantizar la seguridad del cultivo.

2. Diseñar, desarrollar y poner a punto un sistema de control para la corrección del desplazamiento lateral de un implemento agrícola para el control mecánico de malas hierbas, permitiendo errores de menos de 0,5 cm. El implemento se acopla al vehículo autónomo utilizando un enganche estándar de 3 puntos, que contiene un sistema de accionamiento que permite al implemento modificar su posición lateral con respecto al vehículo autónomo. La posición lateral del implemento se debe modificar debido a las imperfecciones del suelo y la siembra así como el desplazamiento del vehículo autónomo debido a las correcciones en la trayectoria. Las correcciones de la posición relativa del

implemento con respecto al vehículo autónomo se deben hacer para evitar daños a los cultivos y para garantizar de este modo un tratamiento eficaz.

3. Investigar y desarrollar una arquitectura de control para permitir que la percepción y actuación se sincronicen en tiempo real, a fin de lograr un ahorro de alrededor del 75% de los insumos agrícolas, que es uno de los principales objetivos del proyecto RHEA.
4. Diseñar, desarrollar e implementar una arquitectura de control que proporcionará la posibilidad de añadir otros elementos para la expansión del sistema inicial, que incorpora diferentes sistemas de comunicación, sensores y actuadores, además de permitir otro tipo de implementos agrícolas. Para lograr esto, la arquitectura de control debe ser lo suficientemente flexible, pero robusta para permitir la fácil integración de otros dispositivos sin disminuir su rendimiento.
5. Diseñar, desarrollar e implementar los elementos necesarios para permitir que un operador humano pueda controlar de forma remota la unidad móvil autónoma, manteniendo los niveles de seguridad requeridos para proteger el sistema y el medio ambiente.
6. Diseñar y desarrollar un entorno de simulación para estudiar y evaluar el efecto de robots móviles en la ejecución de técnicas de agricultura de precisión. Esta herramienta permitirá a los diseñadores realizar un paso intermedio en la validación de los desarrollos que se derivan de esta investigación antes de ser implementado en un escenario real agrícola. El entorno de simulación debe proporcionar algunas capacidades para abordar los conocimientos, tanto agrícolas como de robótica, a través de herramientas computacionales avanzadas (MATLAB, Webots) para representar la información de una manera fácil y amigable. Además, los modelos necesarios deben ser desarrollados e integrados para emular las condiciones de operación de un sistema agrícola totalmente autónomo (vehículos autónomos e implementos, variabilidades del campo y de los cultivos, etc.).
7. Verificar y validar la arquitectura de control y los algoritmos desarrollados e implementados en las unidades agrícolas autónomas reales en un entorno de trabajo agrícola real.

8. Difundir los resultados para que la comunidad científica y técnica, que participan en el desarrollo de vehículos autónomos, pueden beneficiarse de los progresos.

3. Contribuciones de este trabajo de tesis

Junto con la actividad realizada durante la investigación descrita en este trabajo de tesis, se han publicado varias contribuciones importantes en diversas revistas de alto índice de impacto. Las principales contribuciones entran en el ámbito de las flotas de robots autónomas orientadas hacia la ejecución de tareas agrícolas, así como en el área orientada hacia la integración de sistemas sensoriales y de actuación de vehículos autónomos agrícolas, donde se han producido tres publicaciones principales. Además, otras seis contribuciones significativas han resultado de la integración y la colaboración entre diferentes universidades y grupos de investigación, así como estancias de investigación en centros internacionales, lo que ha permitido que el trabajo realizado forme parte de otras publicaciones importantes en las áreas de visión por computador e ingeniería agrícola. A continuación se describe cada contribución en detalle.

- **Contribuciones principales:**

La robótica aplicada a la agricultura es un campo muy complejo, donde una gran cantidad de conocimientos de diversas áreas de investigación debe combinarse e integrarse para lograr una aplicación que funcionando de forma fiable, llegue a los agricultores y sea capaz de realizar la tarea para la que fue diseñada. Un elemento que permite la integración de nuevos conocimientos es el uso de herramientas de simulación, que también permite, durante el desarrollo de la investigación, realizar una evaluación previa en las primeras etapas del diseño, así como la evaluación de nuevos desarrollos tanto en robótica como en agricultura.

Partiendo de esta premisa, una de las principales aportaciones derivadas de la investigación es el desarrollo de un entorno de simulación que pretende cerrar el lazo entre la robótica y el conocimiento agrícola, permitiendo al usuario desarrollar nuevos sistemas robóticos y algoritmos basados en diferentes niveles de configuración, dependiendo de qué parte del conocimiento se desee proporcionar. Esta herramienta computacional se denomina "*Simulation Environment for Precision Agriculture Tasks using Robot Fleets*", o SEARFS por sus siglas en inglés, y su objetivo principal es permitir el estudio y evaluación de la ejecución de tareas agrícolas que pueden ser realizadas por una flota de robots autónomos. El entorno de simulación se basa en una herramienta comercial de simulación de robots móviles que permite el análisis de los resultados, la cooperación y la interacción de un conjunto de robots autónomos, mientras se simula la ejecución de acciones específicas en un campo de cultivo en tres dimensiones (3D). El entorno de simulación es capaz de simular los nuevos avances tecnológicos, tales como GPS, GIS, control automático, teledetección remota, así como los desarrollos en el campo de la informática móvil, que permitirá la evaluación de nuevos algoritmos derivados de técnicas apropiadas para agricultura de precisión. Esta contribución fue publicada en la revista *Industrial Robot* y se describe en detalles en el capítulo 3.

Emmi, L., Paredes-Madrid, L., Ribeiro, A., Pajares, G., Gonzalez-de-Santos, P. 2013. Fleets of robots for precision agriculture: A simulation environment. *Industrial Robot*, *40*(1), pp. 41-58.

Tal como se ha presentado en el apartado anterior, debido a los recientes avances tecnológicos que han surgido en los últimos 20 años, la integración de varios vehículos autónomos formando una flota, y en particular los robots agrícolas, dotados de altas capacidades sensoriales, de actuación y procesamiento ha facilitado y ha permitido una mayor precisión al ejecutar diversas tareas (Åstrand et al., 2002; Bakker et al., 2011; Li et al., 2009; Pedersen et al., 2006; Stentz et al., 2002). Ejemplos de tales avances tecnológicos son sensores especializados (visión artificial, navegación cinética satelital en tiempo real – o RTK-GPS por sus siglas en inglés-, equipos basados en láser y dispositivos de medida inercial –o IMU por sus siglas en inglés-), actuadores (pistones hidráulicos y lineales y motores eléctricos rotatorios), y equipos electrónicos (ordenadores integrados, PCs industriales y PLCs). Sin embargo, la mayoría de las aplicaciones de robótica orientadas a la ejecución de tareas agrícolas, que se pueden encontrar tanto en la literatura científica como en productos comerciales, se centran en la solución de un problema específico, por ejemplo, guiado autónomo u operación de cultivo autónoma (Auat Cheein et al., 2013; Bakker et al., 2010a; Blackmore et al., 2001; Fountas et al., 2007; Katupitiya et al., 2007; Rovira-Más, 2010a), y sólo unos pocos han propuesto la realización de un sistema agrícola totalmente autónomo (Bergerman et al., 2012; Blackmore et al., 2004; Johnson et al., 2009; Kohanbash et al., 2012; Moorehead et al., 2012; Nørremark et al., 2008; Pilarski et al., 2002). Otra importante contribución de este trabajo de tesis es la propuesta de una arquitectura hardware capaz de integrar diferentes sistemas de sensores y de actuación desarrollados por diversos grupos de investigación, así como diferentes tipos de equipos comerciales con el objetivo de estructurar e integrar un sistema agrícola totalmente autónomo como parte de una flota de robots.

Para lograr la estructura de la arquitectura propuesta, se hizo un análisis de los requisitos de un sistema agrícola totalmente autónomo, además de un análisis de los requisitos de tales sistemas autónomos trabajando en conjunto en una flota de robots. La arquitectura propuesta se ha diseñado para ser flexible y capaz de integrar varios protocolos estándares de comunicación que son comunes en aplicaciones agrícolas de alta tecnología. Además, otro requisito de la arquitectura propuesta era modularidad, es decir, proporcionando los ajustes adecuados de las interfaces entre los sensores y los dispositivos y la organización adecuada de la percepción, el procesamiento y la actuación de estos tipos de sistemas debido a la gran variedad de tecnologías disponibles. Esta contribución fue publicada en la revista *The Scientific World Journal*, cuyos fundamentos se describen en el capítulo 4.

Emmi, L., Gonzalez-de-Soto, M., Pajares, G., Gonzalez-de-Santos, P. 2014. New Trends in Robotics for Agriculture: Integration and Assessment of a Real Fleet of Robots. *The Scientific World Journal*, *2014*, pp. 1-21.

Ampliando la idea de la implementación e integración de un sistema agrícola totalmente autónomo, y usando la arquitectura propuesta como base, la tercera aportación principal de este trabajo de tesis es la configuración de un sistema completo, integrando percepción, actuación, y toma de decisiones como subsistemas para un sistema agrícola autónomo que trabaje en cultivos cuya plantación se estructure con surcos anchos reales, como es el caso del maíz. Esto se ha realizado mediante la selección, ordenación, integración y sincronización de los subsistemas de percepción, actuación, y toma de decisiones, lo que proporciona un modelo estructurado y probado para un vehículo completamente autónomo para aplicaciones agrícolas. Los resultados experimentales derivados de esta contribución demuestran el éxito y el rendimiento del sistema integrado en las tareas de guiado y control de malas hierbas en un campo de maíz, lo que indica su utilidad y eficacia.

La integración desarrollada en este estudio tenía por objeto permitir que los diversos sistemas que constituyen el vehículo autónomo trabajen conjuntamente mediante la sincronización de la información del sistema de percepción (visión artificial, RTK-GPS e IMU) utilizando un sistema de actuación especializado (control de malas hierbas en sitio específico para cultivos de maíz), así como el guiado del propio vehículo. Los resultados obtenidos en este estudio permiten la caracterización del sistema agrícola totalmente autónomo, además de definir sus capacidades y limitaciones. Además, se midieron la precisión y los retardos asociados, tanto del sistema de visión como de actuación, lo que permite la evaluación de la capacidad del sistema agrícola completo para llevar a cabo un tratamiento eficaz, es decir, la cantidad de producto que puede ahorrarse, que es un objetivo último definitivo de la agricultura de precisión. Esta contribución se publicó en la revista *Sensors*, y se describe en el capítulo 5.

Emmi, L., Gonzalez-de-Soto, M., Pajares, G., Gonzalez-de-Santos, P. 2014. Integrating sensory/actuation systems in agricultural vehicles. *Sensors*, *14*, pp. 4014-4049.

- **Otras contribuciones:**

Además de las principales contribuciones que figuran en el apartado anterior, el trabajo realizado durante la investigación también ha generado otras aportaciones fruto de los trabajos realizados en colaboración con otros centros de investigación y universidades.

Teniendo en cuenta que el trabajo realizado y presentado en esta memoria de tesis contiene elementos significativos relativos a la integración entre los sistemas sensoriales y de actuación, un gran esfuerzo se realizó conjuntamente con el grupo de investigación ISCAR de la Facultad de Informática de la Universidad Complutense de Madrid (UCM). Este trabajo, que representa una contribución principal en cooperación con otros investigadores participantes en el proyecto RHEA, permitió la ejecución de diversas pruebas de campo con un vehículo autónomo agrícola para realizar ajustes y validar el ensamblaje y los algoritmos desarrollados por el equipo de investigación de la UCM. En estos trabajos se utilizaron los principales elementos de la arquitectura presentada en (Emmi et al., 2014a; Emmi and Gonzalez-de-Santos, 2012), que están relacionados con la adquisición, la sincronización, y la ejecución de los algoritmos de procesamiento de imagen. La integración de estos algoritmos para su ejecución en tiempo real constituye el principal aporte de esta investigación. Estas contribuciones fueron publicadas en las revistas *Sensors* y *Expert Systems with Applications* como parte de los sistemas completos, cuyos fundamentos se encuentran integrados en los capítulos 3, 4 y 5.

Romeo, J., Guerrero, J.M., Montalvo, M., Emmi, L., Guijarro, M., Gonzalez-de-Santos, P., Pajares, G. 2013. Camera Sensor Arrangement for Crop/Weed Detection Accuracy in Agronomic Images. *Sensors*, *13*, pp. 4348-4366.

Guerrero, J.M., Guijarro, M, Montalvo, M., Romeo, J., Emmi, L., Ribeiro, A., Pajares, G. 2013. Automatic expert system based on images for accuracy crop row detection in maize fields. *Expert Systems with Applications*, *40*(2), pp. 656-664.

Montalvo, M., Guerrero, J.M., Romeo, J., Emmi, L., Guijarro, M, Pajares, G. 2013. Automatic expert system for weeds/crops identification in images from maize fields. *Expert Systems with Applications*, *40*(1). pp. 75-82.

Otras contribuciones también derivadas del trabajo en cooperación con otros integrantes del consorcio del proyecto RHEA fue la evaluación de la utilización de diversas soluciones de localización por satélite para la orientación autónoma de vehículos desarrollados para aplicaciones agrícolas. Esta evaluación se llevó a cabo mediante el uso de la arquitectura de control desarrollada en este trabajo de tesis, y que deriva una publicación en la revista *Applied Engineering in Agriculture*:

Carballido, J., Perez-Ruiz, M., Emmi, L., Agüera, J. 2014. Comparison of Positional Accuracy between RTK and RTX GNSS Based on the Autonomous Agricultural Vehicles under Field Conditions. *Applied Engineering in Agriculture*, *30*, pp. 361–366.

Además de éstas, otras contribuciones menores han surgido de la investigación, siendo también plasmadas en este trabajo de tesis. Una de ellas, publicada en el congreso *First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, presenta un controlador para el posicionamiento lateral de vehículos agrícolas basado en lógica borrosa y uno de los procedimientos para integrar nuevos conocimientos, sobre todo para controladores, en el entorno de simulación SEARFS:

Emmi, L., Pajares, G., Gonzalez-de-Santos, P. 2012. Integrating robot positioning controllers in the SEARFS simulation environment. In *Proceedings of the First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, Pisa, Italy, 19-21 September, 2012, pp. 151-156.

Otro aportación, presentada en la misma conferencia RHEA-2012, plantea una primera aproximación de la arquitectura publicada posteriormente en (Emmi et al., 2014a).

Emmi, L., Gonzalez-de-Santos, P. 2012. Hardware architecture design for navigation and precision control in autonomous agricultural vehicles. In *Proceedings of the First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, Pisa, Italy, 19-21 September, 2012, pp. 217-222.

Otra contribución, también presentada a la conferencia RHEA-2012, introduce el uso de algunos elementos del entorno de simulación SEARFS para el análisis de la dependencia de la precisión de la densidad de verde en la detección de cultivos y malas hierbas sobre la base de las variaciones en el ángulo de inclinación de la cámara:

Guerrero, J.M., Romeo, J., Emmi, L., Montalvo, M., Guijarro, M, Pajares, G., Gonzalez-de-Santos, P. 2012. Influence of the vision system pitch angle on crop and weeds detection accuracy. In *Proceedings of the First RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture*, Pisa, Italy, 19-21 September, 2012, pp. 319-324.

Además, este trabajo ha permitido la realización de una estancia de investigación en la Universidad de Pisa, produciendo una contribución al diseño de un implemento mecánico-térmico para el control de malas hierbas, y que fue utilizado en este trabajo de tesis para validar la integración de un sistema de percepción con dicho sistema de actuación mediante el arquitectura de control presentada. Esta contribución fue publicada en la conferencia *Second International Conference on Robotics and associated High-technologies and Equipment for Agriculture and forestry*:

Frasconi, C., Martelloni, L., Fontanelli, M., Raffaelli, M., Emmi, L., Pirchio, M., Peruzzi, A. 2014. “Design and full realization of physical weed control (PWC) automated machine within the RHEA project”. In *Proceedings of the Second International Conference on Robotics and associated High-technologies and Equipment for Agriculture and forestry (RHEA-2014)*. Madrid, Spain, 21-23 May, 2014, pp. 3-12.

Por último, algunas contribuciones también se han publicado en varias conferencias internacionales, donde se presentó la idea principal del proyecto RHEA:

Peruzzi, A., Raffaelli, M., Emmi, L., Fontanelli, M., Frasconi, C., Gonzalez-de-Santos, P. 2011. "The Rhea Project: a fleet of autonomous robot able to perform physical weed control in herbaceous and vegetable crops". In *Proceedings of the V International Scientific Symposium "Farm Machinery and Process Management in Sustainable Agriculture"*- Lublin, Poland, 23-24 November 2011, pp. 119-122.

Peruzzi, A., Vieri, M., Emmi, L., Raffaelli, M., Fontanelli, M., Rimediotti, M., Frasconi, C., Sarri, D., Lisci, R., Gonzalez-de-Santos, P. 2011. "Il progetto RHEA: definizione e gestione delle attrezzature per il controllo fisico delle infestanti da implementare su una flotta di robot autonomi". In *Proceedings of the Convegno Nazionale A.I.I.A. – Gestione e controllo dei sistemi agrari e forestali,* Belgirate, Italy, 22-24 Settembre 2011, memoria 61, pp. 7.

Gonzalez-de-Santos, P., Vieri, M., Ribeiro, A., Raffaelli, M., Emmi, L., Fontanelli, M., Rimediotti, M., Frasconi, C., Sarri, D., Peruzzi, A. 2011. "Il progetto RHEA: una flotta di robot autonomi per la gestione mirata del controllo chimico e non chimico delle infestanti su specie erbacee di pieno campo e dei trattamenti alle colture arboree". In *Proceedings of the Convegno Nazionale A.I.I.A. – Gestione e controllo dei sistemi agrari e forestali*, Belgirate, Italy , 22-24 Settembre 2011, memoria 62, pp. 6.

A continuación se incluyen los principales resultados y conclusiones derivados de la investigación.

4. Resultados y Conclusiones

El concepto de sistemas agrícolas totalmente autónomos, así como el uso de flotas de robots en tareas agrícolas, ha ido ganando cada vez más atención en las últimas dos décadas, gracias a las nuevas tecnologías para el guiado de vehículos e implementos. La integración de los avances tecnológicos en la agricultura de precisión ha sido un factor importante impulsor de niveles más altos de automatización en la agricultura, si bien es cierto que aún queda mucho trabajo por hacer en este sentido. La investigación realizada ha permitido el desarrollo de la configuración e integración de un sistema agrícola totalmente autónomo basado en una flota de robots, con aplicaciones específicas en el control autónomo de malas hierbas. Este trabajo de tesis cubre los aspectos derivados de dicha integración que van desde el desarrollo de un entorno de simulación, hasta el desarrollo y evaluación de algoritmos, y la ejecución de pruebas en cultivos agrícolas sobre condiciones reales para demostrar las capacidades y limitaciones de la integración de la robótica capaz de realizar tareas agrícolas de forma autónoma. El trabajo descrito en esta memoria de tesis se centró en aplicaciones para el control de malas hierbas en el marco del proyecto RHEA; sin embargo, en vista de los resultados obtenidos su uso se puede extender a muchos otros tipos de aplicaciones agrícolas.

- **Entorno de simulación para una flota de robots agrícola**

Dadas las necesidades de combinar robótica y conocimientos agrícolas, el uso de un entorno de simulación fue de gran ayuda para dar los primeros pasos hacia la integración de un sistema agrícola totalmente autónomo basada en una flota de robots. El entorno de simulación SEARFS presentado en el capítulo 3 fue la primera contribución principal que ayudó en la aplicación de técnicas de agricultura de precisión, que permite su evaluación en un mundo virtual en 3D realista. Este entorno de simulación fue un primer paso en el desarrollo de una flota operativa de robots para la agricultura de precisión que podrían cooperar para ejecutar una amplia gama de tareas de forma simultánea. El entorno de simulación también permitió la validación de nuevas arquitecturas de control para los sistemas agrícolas multirobot.

- **Arquitectura de control y el controlador principal de un sistema agrícola totalmente autónomo**

Uno de los elementos más importantes que permitirán la implementación de un sistema agrícola totalmente autónomo es el controlador principal, que puede permitir la comunicación e integración de los distintos subsistemas (tanto unidades comercialmente disponibles como prototipos) necesarios para el guiado autónomo, el control de malas hierbas mediante su localización específica y seguridad entre numerosas otras tareas. Una arquitectura de control híbrida centrada en un controlador principal basado en un sistema cRIO resultó ser el enfoque más adecuado para los sistemas utilizados y descritos en esta memoria de tesis, donde dicho controlador era imperativo para la adquisición de los principales sistemas sensoriales que debían ser integrados. Este enfoque, descrito en el capítulo 4, permitió la combinación de la información proveniente del sistema sensorial para mejorar el rendimiento general y proporcionar una mayor precisión, robustez y datos complementarios al tiempo que reduce el número de sistemas y dispositivos hardware.

Las configuraciones de los sistemas de percepción, toma de decisiones y de actuación se definieron para construir un vehículo autónomo para aplicaciones agrícolas, específicamente dedicado al control de malas hierbas en cultivos con los surcos suficientemente espaciados[1], como es el maíz. Se utilizaron dispositivos comerciales con protocolos de comunicación estándar para el intercambio de mensajes entre los sistemas. Este enfoque ha demostrado ser fiable para un gran número de horas de trabajo, y los algoritmos de procesamiento han resultado ser suficientemente flexibles y escalables, con capacidad para adaptarse a diferentes situaciones, tanto de los propios sistemas como del entorno que perciben. La integración de los sensores y actuadores que se presentan en esta memoria de tesis fue evaluada positivamente por el consorcio RHEA. Los resultados experimentales obtenidos de los vehículos individuales indicaron que el diseño es compatible con una flota de robots, que era el objetivo principal de la investigación. La arquitectura propuesta, que incorpora tres sistemas principales, fue diseñada para el control de malas hierbas en campos de maíz, pero gracias a su diseño flexible y abierto, los mismos vehículos se pueden utilizar para otras tareas agrícolas. Sin embargo, para ello será necesaria la adaptación de nuevos elementos y procesos relacionados para las tareas previstas. Por ejemplo, estos sistemas podrían utilizarse para tratamientos localizados en cultivos de ajo, tomates u otros cultivos con distancias suficientes entre los surcos.

Sobre la base de los requerimientos para un sistema agrícola totalmente autónomo presentado en esta memoria de tesis, se diseñó una arquitectura de control híbrida basada en un controlador centralizado. Se recibieron diversos comentarios por parte de los socios de RHEA y otros investigadores en conferencias a lo largo del desarrollo de este trabajo de tesis que cuestionó la selección del controlador principal y el diseño de la arquitectura. Es interesante notar que la mayoría de estos comentarios estaban relacionados con la no utilización de ROS como base para el diseño de la arquitectura, los sistemas de comunicación, y otros desarrollos.

[1] Nota del autor: con el término “surcos suficientemente espaciados” se intenta describir el término en inglés “*wide-row crops*”, pretendiendo definir que el cultivo tiene los surcos suficientemente separados para la maximización del espacio.

Está claro que ROS es una herramienta poderosa para el desarrollo de sistemas robóticos que agiliza la comunicación entre dispositivos (nodos), ya sea dentro de los mismos dispositivos o en un sitio remoto donde se ejecuta el software. Otro factor que favorece el uso de ROS es la capacidad de los usuarios para compartir sus desarrollos ya que existe una gran comunidad compuesta principalmente por investigadores y estudiantes. El hecho de compartir códigos, controladores y algoritmos tiene el potencial de reducir en gran medida el esfuerzo a realizar para implementar nuevos sistemas. Dado el nivel de integración que se lleva a cabo en los desarrollos realizados en la presente investigación, ROS parecía ser otra opción a tener en cuenta durante la fase de diseño.

A pesar de ello, gracias a la experiencia adquirida durante el desarrollo del proyecto RHEA y demostrando las capacidades y limitaciones de la arquitectura a través de los resultados experimentales en campos de cultivo reales, se puede concluir que el diseño finalmente adoptado para la arquitectura de control, así como la selección del controlador principal, ha resultado ser un enfoque de integración totalmente válido. Por otra parte, los experimentos realizados han demostrado que el rendimiento del sistema se podría mejorar en relación con la precisión en la ejecución del tratamiento y control, si algunos de los elementos externos (dispositivos distribuidos) están integrados en el controlador principal. Básicamente, cualquier tarea que requiera el cumplimiento estricto de tiempo de ejecución (adquisición de datos de los sensores, correlación de datos y actuación) puede integrarse en el controlador principal para proporcionar mejoras en los tiempos de ejecución y rendimiento.

En ocasiones no se aprovechan al máximo las capacidades en tiempo real del controlador principal con algunas funciones y algoritmos que no pueden mantener un tiempo de ejecución consistente, en particular con respecto al procesamiento de imágenes. En estos casos, para mejorar el rendimiento de procesamiento de imagen y aumentar la capacidad para procesar más imágenes por segundo, la ejecución de los algoritmos se debe realizar utilizando hardware dedicado en lugar del controlador principal seleccionado. Sin embargo, para la aplicación basada en RHEA, donde no se requiere una alta tasa de imágenes por segundo, la integración del procesamiento de imágenes dentro del controlador principal resulta ser aceptable, lo que reduce la cantidad de hardware a utilizar, a la vez que proporciona una mejor geo-referenciación de las imágenes, permitiendo a otros sistemas, integrados dentro del controlador principal disponer de dichas imágenes con otra finalidad, por ejemplo, de algoritmos de detección de obstáculos.

Además de las ventajas en la ejecución de tareas en tiempo real dentro del controlador principal, otros aspectos tales como la robustez, la flexibilidad, la escalabilidad y la modularidad permiten que una unidad agrícola totalmente autónoma sea integrada y probada en un entorno real. Esto es debido a que el esfuerzo de integración involucró a varios grupos de investigación diferentes, cada uno trabajando con un lenguaje de programación específico (por ejemplo, C ++, Matlab, Python), de forma que la selección del controlador principal no fue un impedimento para llevar a cabo estas actividades, ya que LabVIEW es capaz de integrar y ejecutar código externo.

Una de las características prometedoras, derivada del hecho de utilizar el controlador principal para la integración de un sistema agrícola totalmente autónomo, es la capacidad para la gestión de diversos niveles de programación, abarcando desde el control de entradas y salidas tanto analógicas como digitales (con la ayuda de un módulo FPGA) a la implementación de algoritmos de toma de decisiones y control inteligente, así como de procesamiento de imágenes e interfaces de usuario, todas ellas utilizando el mismo entorno de desarrollo (LabVIEW).

- **Arquitectura de control en un sistema real: pruebas y análisis**

En el trabajo desarrollado, la arquitectura de control y el controlador principal se implementaron en las unidades móviles de la flota RHEA, con el objetivo de llevar a cabo el control de malas hierbas de forma localizada en tres escenarios diferentes. Cuando se trabaja en condiciones reales de campo con más de un robot a la vez, particularmente cuando los robots son de alguna manera diferente entre sí (como ocurre con las tres GMUs del proyecto RHEA que llevan tres implementos diferentes, como se muestra en la Figura 4.3), las dificultades son mayores y más complejas que en una aplicación multi-robot en un entorno homogéneo y cerrado. Una de las principales dificultades de integración de la arquitectura de control en las unidades de RHEA es la obtención de una configuración adecuada para cada unidad. Debido a que los prototipos de unidades GMU desarrollados, requiriendo distintos elementos y dispositivos para un correcto funcionamiento simultáneo, el controlador principal era necesario para gestionar con solidez las comunicaciones y fallos en los dispositivos. Esto se logró gracias a las características intrínsecas del dispositivo cRIO seleccionado, que consiste en un ordenador industrial que ofrece grandes beneficios de hardware y software en entornos complejos y exigentes, tales como los encontrados en este tipo de aplicación.

Una de las ventajas de la arquitectura para la integración de los distintos dispositivos desarrollados por los diferentes socios, era la posibilidad de modificar, configurar y ajustar los parámetros y algoritmos en tiempo real. Esto fue posible gracias a LabVIEW, que genera código paralelo para cada subrutina o función con una interfaz fácil de usar a la que puede acceder el operario en tiempo de ejecución. Sin embargo, el uso de esta interfaz presenta ciertos inconvenientes durante la comunicación inalámbrica, donde aparecieron fallos y problemas a la hora de establecer y mantener conexiones abiertas. Una conclusión que se puede extraer de esta experiencia es que el procedimiento de depuración no era apropiado para la aplicación, dada la naturaleza y el tipo de conexiones entre los usuarios y los sistemas cRIO. Sin embargo, tras superar los procesos de prueba y depuración, el rendimiento del sistema fue el esperado.

Con respecto a las comunicaciones y el intercambio de datos entre los dispositivos de la red y/o rutinas en un único dispositivo, la experiencia nos ha enseñado que un protocolo de comunicación simple nos permite mantener un mayor control y rendimiento adecuado del sistema. Por ejemplo, una ventaja importante de LabVIEW es la comunicación entre procesos en tiempo real dentro del controlador principal, aunque esto no fue siempre el caso con respecto a la comunicación con otros dispositivos que ejecutan LabVIEW. Por lo tanto, el protocolo de comunicación en RHEA para el seguimiento y control de la flota en la estación base proporcionó mayores beneficios que las variables de LabVIEW para el intercambio de datos en red. Además, los controladores necesarios para la comunicación con los dispositivos COTS, tales como cámaras, receptores GPS y láser, ya estaban disponibles y requirieron de muy pocas modificaciones para adecuarse a la aplicación gracias a la comunidad de desarrolladores y bibliotecas especializadas existentes.

- **Conclusiones específicas**

- Guiado del vehículo en cultivos con surcos anchos

Basado en el sistema de percepción presentado en el capítulo 5, se implementó y diseñó un algoritmo para el seguimiento de líneas de cultivo en las unidades móviles del proyecto RHEA. Este algoritmo ajusta una línea recta original que cruza el campo (dada por la misión que se planea con antelación), y realiza correcciones menores utilizando el sistema de percepción visual. Fue posible obtener un error promedio de aproximadamente ±5 cm cuando se siguen las líneas de cultivo, que es ligeramente mayor que el error propuesto (±2 cm). Sin embargo, en ninguna ocasión ni el vehículo ni el implemento causaron ningún daño al cultivo y la detección se realizó con éxito en aproximadamente el 89% de los casos. Dada la complejidad del sistema, diversos elementos afectaron el rendimiento del controlador, como se describe a continuación.

a) **Disposición de la cámara:** debido a que la disposición de la cámara en el tractor (Romeo et al., 2013) se encontraba situada a una altura y distancia considerable sobre las líneas de cultivo (véase la Figura 5.4), la precisión relativa al cálculo del desplazamiento lateral del vehículo con relación al cultivo fue ligeramente mayor que en otras aplicaciones existentes en la literatura que lo cuantifican en ±2 cm, en las que la cámara se encuentra a sólo unos centímetros por encima del suelo. Además, la disposición de la cámara afecta significativamente la exactitud del cálculo según sea la diferencia del ángulo entre el vehículo y el cultivo dado que esta información está proporcionada por los píxeles más lejanos en la región de interés, o ROI como sus siglas en inglés, según un eje longitudinal (que no contienen la misma cantidad de información que los píxeles que representan la zona de la ROI más cercana al vehículo).

b) **Estado de crecimiento del cultivo:** debido al procedimiento para la detección de las líneas de cultivo (Guerrero et al., 2013), si éstos poseen un grado de crecimiento relativamente bajo (con 2 o 3 hojas de maíz por plante), la precisión del cálculo de la posición de las líneas de cultivo con respecto al vehículo es mayor. Por lo tanto, si los cultivos están en su estado de crecimiento temprano (los primeros momentos en los que puede aplicarse el tratamiento mecánico-térmico sobre las malas hierbas), la ocupación del cultivo en las imágenes (la anchura de las plantas) es menor que si el cultivo está en un estado de crecimiento más avanzado (es decir, 5-7 hojas para el maíz).

c) **Geo-referenciación de una imagen:** teniendo en cuenta el procedimiento que se utiliza para asociar una posición GPS con una imagen captada por el sistema de visión y debido a las correcciones que el controlador de seguimiento de trayectorias debe realizar (generando oscilaciones considerables en la postura; véase la Figura 5.12), el cálculo de la diferencia entre el centro de las líneas de cultivo con respecto al centro del vehículo puede alterarse significativamente en algunas ocasiones, siendo el error de ±0,08 m en el peor de los caso, tal y como ha quedado demostrado en los experimentos.

En resumen, se han identificado varios factores que afectan a la capacidad de percepción y el sistema de actuación para el guiado de un vehículo autónomo en un campo de cultivo. Dependiendo de la situación del cultivo y de los sistemas mencionados, esto puede afectar en un incremento del error máximo. Sin embargo, dada la aplicación en la que el sistema se probó (un campo de maíz sembrado a 75 cm, con una posición de inicio y final conocidas para del campo y una ubicación aproximada de algunas de las líneas de cultivo), las características del vehículo y el ancho del tratamiento mecánico, la precisión real obtenida fue suficiente para cumplir con el objetivo específico marcado en el proyecto RHEA de mantener los cultivos a salvo, es decir, libres de daños durante el tratamiento.

- Precisión en el desplazamiento lateral de un implemento para control mecánico de malas hierbas:

Se diseñó, desarrolló y probó un sistema de control para un implemento específico orientado al control mecánico de malas hierbas, tal como se presenta en el capítulo 5. Además se desarrolló un sensor especializado para medir el desplazamiento lateral del implemento con respecto al vehículo. Este sistema fue validado utilizando un láser como dispositivo de medición externo, obteniendo una precisión de aproximadamente ± 0,004 m. Sobre la base de este sistema sensorial y el sistema de actuación, que consta de un pistón hidráulico que actúa sobre unas ruedas de dirección, se implementó un conjunto de dos controladores PID en configuración en cascada. Se llevaron a cabo una serie de pruebas para la sintonización del controlador, obteniendo un error de aproximadamente ±0,01 m y un tiempo de estabilización de 3 s a una velocidad de operación de 0,28 m/s. Además, la creación de este sistema no resultó una tarea fácil, dada la complejidad y la dinámica de la interacción entre el vehículo, el implemento y el terreno, lo que provocó que el implemento oscilase ligeramente alrededor de la posición deseada. Sin embargo, la magnitud de la oscilación fue de aproximadamente 2 ó 3 cm, que se considera relativamente pequeña dado el tamaño del implemento, los errores asociados en el guiado del vehículo y el espacio entre el elemento mecánico (la azada) y el cultivo. Aunque los errores obtenidos fueron superiores al error máximo (0,5 cm) propuesto en el proyecto RHEA, los cultivos se mantuvieron a salvo, suponiendo por tanto un valor de error aceptable.

- Ahorro de producto para implemento para control mecánico de malas hierbas:

Se diseñó e implementó una arquitectura de control para sistemas agrícolas autónomos en la unidad móvil del proyecto RHEA. Esta arquitectura permitió la integración de subsistemas de percepción, actuación, y de toma de decisiones para un sistema agrícola totalmente autónomo configurado para el control mecánico de malas hierbas en maíz. El implemento utilizado para la evaluación de la arquitectura de control consistió en cuatro pares de quemadores para el control térmico de malas hierbas en el espacio situado dentro del surco definido por el cultivo, y elementos mecánicos especializados para el tratamiento del espacio entre las líneas de cultivo. Se realizó una caracterización del sistema teniendo en cuenta los retardos intrínsecos en la activación de los quemadores (relés y válvulas) y retrasos en las comunicaciones. Para estas pruebas, se utilizó el controlador GMUC del proyecto RHEA como el sistema de control para el implemento. Los resultados en detalle se presentan en el capítulo 5, donde se analizan tres situaciones (uso común, ideal y real), para un campo específico con una distribución específica de malezas, ahorrando un 65,1% de producto (propano). Se pueden extraer dos interpretaciones en relación a estos resultados:

1) Los retardos de tiempo son más altos de lo esperado, lo que afecta considerablemente en el ahorro de producto. Los retrasos en la comunicación entre el controlador principal y el controlador del implemento se pueden reducir a casi una décima de segundo, si se utiliza otro tipo de comunicación o si el control de las válvulas y relés está centralizado en el controlador principal, tal como se propone en el capítulo 4. Esto puede reducir los retrasos en la ignición y extinción de los quemadores en la mitad de los valores actuales. Realizando el mismo análisis que se presenta en la Tabla 5.7, se puede obtener un ahorro de aproximadamente el 73,5% (véase Tabla 6.1), que es un valor muy próximo al objetivo establecido.

2) La distribución espacial de las malas hierbas en el campo es un factor que afecta significativamente al ahorro de producto, dadas las características no ideales del sistema de actuación (relés y válvulas). Esto obliga a aplicar un encendido adelantado de los quemadores con respecto al borde del rodal de malas hierbas y el retraso del apagado con respecto al extremo opuesto del mencionado rodal. Por lo tanto, el ahorro de producto es una función del tamaño del rodal y su distribución, por ejemplo, dimensiones o distancia entre rodales.

El proceso por el cual las malas hierbas se extienden en un campo de cultivo es muy complejo ya que las mismas son organismos vivos que interactúan con el suelo según el clima. Por lo tanto, la distribución espacial de las malas hierbas es difícil de simular y expresar matemáticamente, tal y como se discutió en el capítulo 3.

- Conclusiones respecto a la extensión de la arquitectura de control

Se desarrolló e implementó una arquitectura de control para cada uno de los robots individuales y robots que trabajan en flotas para mejorar la fiabilidad, reducir la complejidad y los costes, a la vez que permitir la integración de software de diferentes desarrolladores. El controlador principal, que constituye el núcleo de la arquitectura, permitió la incorporación directa de un gran número de módulos hardware/software, así como la expansión de sus capacidades de adquisición de datos, de control y de comunicación. Esto incluye las siguientes capacidades:

1. Ethernet: disponibilidad de módulos de comunicación inalámbrica WLAN de NI y conmutador Ethernet.
2. Láser: conectado a través de Ethernet o módulos específicos de NI.
3. Buses de comunicación industriales: bus CAN y bus ISO se pueden integrar a través de las interfaces CAN de NI.
4. Unidades inerciales: conectadas a través de módulos seriales de NI.
5. Módulos de E/S general, digitales y analógicas NI.

Otra cualidad del controlador principal es la posibilidad de incorporar un chasis esclavo para ampliar su capacidad para añadir módulos en un espacio físico diferente al del controlador principal, el cual permite que los módulos para el control de un implemento agrícola puedan llevarse a bordo del vehículo. El chasis de expansión se comunica con el controlador principal a través de EtherCAT, que es una tecnología abierta de alto rendimiento basada en Ethernet de bus de campo comúnmente utilizada en la automatización industrial.

El capítulo 4 presenta la evolución del sistema de computación RHEA basado en la arquitectura de control, que ha demostrado ser flexible y robusto, mientras se mantiene el rendimiento en tiempo real para los distintos elementos integrados en dicha arquitectura (tanto dentro del controlador principal como en los dispositivos distribuidos).

Los principales resultados obtenidos en relación con la arquitectura de control del sistema real propuesto son los que se muestran a continuación.

1) La primera prueba de evaluación se centró en la comparación tanto de la adquisición de imágenes como del procedimiento de procesamiento del sistema de detección de malas hierbas o WDS mediante el uso de la arquitectura propuesta (véase Figura 4.8) con los obtenidos del esquema original de RHEA (véase Figura 4.5). Los resultados obtenidos se presentan en la Tabla 4.1, y se puede concluir que hemos mantenido el rendimiento requerido del sistema, reduciendo el hardware y desarrollando solo un pequeño número de interfaces de comunicación.

2) Una evaluación más del sistema se llevó a cabo mediante la eliminación del controlador GMUC a cargo del guiado del vehículo y la implementación de dichos algoritmos de seguimiento de trayectorias en el controlador principal. En este caso, se evaluaron las capacidades del sistema para reaccionar a cambios tanto en la trayectoria y la velocidad del vehículo, que se mide como el número de mensajes enviados para controlar tanto la velocidad y la dirección del vehículo. El esquema original RHEA define al sistema de guiado como una arquitectura deliberativa, en el que la planificación de trayectorias se realiza por el controlador principal (basado en una misión predefinida y la información del sistema de percepción) y el GMUC ejecuta dicho plan. La arquitectura propuesta cambia esta configuración en una arquitectura híbrida, donde, en situaciones críticas (por ejemplo, evitar obstáculos, guiado en el cultivo, procedimientos de seguridad), se mejoran las capacidades del vehículo para cambiar la posición y orientación.

3) Como prueba final para validar el uso de la arquitectura propuesta en una flota de robots orientados a tareas agrícolas, se evaluó la implementación de un método para evitar colisiones entre unidades. La Figura 4.14(a) muestra el resultado del algoritmo de detección de colisión para un instante de tiempo entre los primeros 20 segundos de la misión en general, durante el cual una posible colisión entre las unidades GMU2 y GMU3 está presente, y por lo tanto la unidad GMU3 tomará más tiempo para llegar al otro extremo del campo. Esta es la situación que se presenta en la Figura 4.14(b), en el que las unidades GMU1 y GMU2 están realizando la vuelta para volver al campo y otra posible situación de colisión está presente. En esta situación, el supervisor de la flota permite continuar con su sub-misión a la unidad GMU1 mientras se detiene el movimiento de la unidad GMU2 hasta que desaparezca la situación de colisión. Además de las pruebas realizadas para evitar colisiones con la configuración maestro-esclavo, se realizaron pruebas con la

configuración del proyecto RHEA original (véase la Figura 4.4), y como se esperaba, se obtuvieron los mismos resultados. Estos resultados confirman el potencial de la arquitectura de control propuesto para una flota autónoma de robots para permitir la reducción de hardware y desarrollo de software mientras se mantiene el rendimiento deseado.

- Conclusiones respecto al control de usuario y seguridad del sistema

En el capítulo 4 se presenta el desarrollo e implementación de una interfaz de usuario para el control y seguimiento de la flota de robots. Esta interfaz, junto con las rutinas de comunicación implementadas en el controlador principal (véase el capítulo 5, sub-sección 5.4.1), permitieron la monitorización del estado y la ubicación de cada unidad y el control del movimiento de los vehículos (iniciar, finalizar, detener, continuar, etc.). Además, el usuario puede cargar una misión predefinida a cada unidad y registrar su posición GPS.

Otro elemento desarrollado e implementado para mantener la seguridad del sistema fue un algoritmo de prevención de colisiones (véase el capítulo 4, sub-sección 4.5.3). Dicho algoritmo de seguridad añade un elemento de cooperación en la flota de robots agrícolas autónomos.

- Conclusiones respecto al entorno de simulación SEARFS

En el capítulo 3 se presentó el desarrollo de un entorno de simulación para una flota de robots diseñada específicamente para agricultura de precisión. Esta herramienta de simulación, llamada SEARFS, se basa en dos sistemas computacionales poderosos (MATLAB y Webots). SEARFS permite la visualización y evaluación de la ejecución de tareas agrícolas por robots autónomos agrícolas equipados con diversos mecanismos de percepción y actuación. Esta evaluación se ha realizado mediante la visualización de un mundo virtual en 3D para representar las características reales de un campo definido (obtenidos mediante mediciones o descargados a través de bases de datos en línea) para el modelado de diferentes variabilidades que pueden afectar a la exactitud en el desempeño de tareas de la flota de robots.

El entorno de simulación SEARFS ha demostrado ser una herramienta útil para validar los conceptos de diseño relacionados con vehículos aéreos y terrestres. También fue una herramienta de gran utilidad para el análisis de misiones con las flotas de robots en el proyecto RHEA. Además, este entorno fue capaz de integrar nuevos elementos y probar nuevos protocolos de comunicación (entre el controlador principal y los periféricos de la GMU) (a) mediante la simulación de campos de cultivo para el análisis y configuración de un sistema de visión por computador (Guerrero et al., 2012), y (b) mediante la adición de nuevos implementos autónomos, vehículos y controladores para la evaluación de sus capacidades, al tiempo que permitía una mejor comprensión de su uso (Emmi et al., 2012).

Para ilustrar los conceptos detrás del proyecto RHEA se generó un video que además se utilizó para evaluar el entorno de simulación SEARFS. Este video se construyó con diferentes capturas obtenidas mientras se ejecuta una simulación de diversas tareas realizadas por las unidades de la flota de robots RHEA (véase Figura 3.12). El video está disponible en la web del desarrollador (SEARFS, 2014).

- **Consideraciones finales**

La arquitectura de control y algoritmos presentados en esta memoria de tesis se han probado, verificado y evaluado positivamente de manera tanto cualitativa como cuantitativa. En mayo de 2013, se completó la flota móvil de tierra, en cuyo momento ya se había instalado todo el hardware y el software. Desde entonces, la flota (equipos y algoritmos) ha sido probada y mejorado casi todos los días (alrededor de seis horas al día, cinco días a la semana, a cuatro semanas al mes, durante aproximadamente 11 meses) con un ciclo de trabajo estimado de aproximadamente el 33,33 %. Eso significa un tiempo total estimando de trabajo de aproximadamente 440 horas. Durante este período, la flota fue probada en tres escenarios reales diferentes en las instalaciones del CSIC-CAR en Arganda del Rey, Madrid (en condiciones de polvo, barro, viento, lluvia, luz cambiante, etc.). Durante estas pruebas se constató un aumento significativo en la fiabilidad, pasando de un tiempo medio entre fallos de 2 minutos en julio de 2013 (el vídeo continuo más largo que se pudo tomar en ese período fue de 2 minutos) a un tiempo superior a 2 horas con problemas menores en mayo de 2014 durante la demostración final del proyecto RHEA. En relación a las conclusiones no registramos el tiempo de trabajo de la flota ni las contingencias ocurridas porque estaban claramente fuera del ámbito de este trabajo.

- **Trabajos futuros**

En esta memoria de tesis se describen y presentan una serie de aportaciones para la configuración y la integración de una flota de robots autónomos diseñados para realizar tareas agrícolas de precisión. Sin embargo, queda mucho trabajo por hacer para llevar estas contribuciones a la industria.

El entorno de simulación presentado en esta memoria de tesis posee un gran potencial que no se ha explotado plenamente. La capacidad de integrar nuevos modelos de robots (tanto de vehículos como implementos), mientras se simulan diversos terrenos, significa que SEARFS será una herramienta poderosa para futuros desarrollos. Uno de los primeros estudios que se deben realizar con SEARFS debería ser la aplicación de varios modelos de distribución espacial de malas hierbas (conociendo que dichos modelos pueden parecerse a la realidad, aunque no llegue a representarla fielmente). Con una mejor caracterización de los implementos de RHEA, también se puede realizar una evaluación más extensa de la capacidad para ahorrar en producto de aplicación para el tratamiento de las malas hierbas. El diseño e implementación de diversos robots de la flota RHEA ya se ha realizado utilizando la herramienta de simulación Webots. Algunos controladores para el guiado de vehículo y control de implementos ya se han desarrollado para continuar con la evaluación y mejora del sistema. La agricultura es una ciencia compleja, y será necesario disponer de muchos modelos diferentes en el sistema (estacionalidad, la efectividad del tratamiento y el costo-beneficio) para ser capaz de simular escenarios económicos para diferentes sistemas de robots agrícolas, lo que puede llevar a la generación de una amplia librería de modelos de simulación

La arquitectura de control presentada en esta memoria de tesis ha demostrado ser suficientemente útil, eficiente y robusta para el control de vehículos autónomos en tareas agrícolas en base a los objetivos planteados en el proyecto, y por tanto totalmente próximos a la realidad agrícola. Sin embargo, se necesitan pruebas adicionales, especialmente en otras posibles aplicaciones en el ámbito agrícola más allá del control de malas hierbas. Todavía existen muchas tareas agrícolas que pueden explotarse, desde la preparación de la tierra para el cultivo hasta la cosecha, donde se han logrado algunos avances con respecto a la automatización. El siguiente paso será un conjunto vehículo-implemento agrícola completamente automatizado que incluya una estructura hardware que elimine las limitaciones de rendimiento que introducen los retardos en las comunicaciones. Una mejora importante será la centralización de las tareas críticas, tales como el control y el guiado del vehículo y del implemento. La extensión de este trabajo podría ayudar a depurar los sistemas desarrollados y llevar los productos automatizados a la industria dedicada a la fabricación de sistemas industriales agrícolas.

En relación con el uso de varios robots para realizar tareas agrícolas, la arquitectura de control presentada en esta memoria ha demostrado su utilidad cuando se necesita la cooperación. El uso de múltiples robots sigue siendo un enfoque sin explotar tanto para tareas heterogéneos como homogéneas. El trabajo futuro se centrará en aumentar las capacidades del controlador principal para ser capaz de reestructurar la misión original, si es necesario, aumentar la eficiencia, mejorar la cooperación, y permitiendo una mejor detección de obstáculos. Además, las posibilidades de conexiones remotas desde otras partes del mundo permitirán que la flota de robots sea supervisada por expertos en el área.

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